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THE UNIVERSITY OF ALBERTA

A STUDY OF CONCRETE FREEZE-THAW DURABILITY AND AIR VOID PARAMETERS

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "A STUDY OF CONCRETE FREEZE-THAW DURABILITY AND AIR VOID PARAMETERS", submitted by Frederick Williamson in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

As a result of the knowledge that concrete freeze-thaw durability depends on the number, size, and spacing of air voids throughout the mass, rather than on the total volume of entrained air voids, study of the air void system of hardened concrete has become concentrated on the determination of significant air void parameters.

This thesis presents the results of an investigation to determine relationships between freeze-thaw durability and air void parameters of hardened concrete. Specifically, the objective of this study was to establish the pattern of the relationships between concrete durability and both the void spacing factor and the specific surface of the voids.

Eighteen concrete mixes, representing six air contents up to approximately nine per cent by volume, and three common cement contents, were prepared and tested during this program. Air void parameters of the hardened concrete, as determined by the lineal traverse method of microscopic examination (A.S.T.M. C 457 - 60T), were measured and related to freeze-thaw durability data obtained from tests performed in accordance with A.S.T.M. procedure C 290 - 57T. Compressive strength data were also obtained for all concrete mixes prepared.

Compressive strength test results verified the well-known relationships involving strength, age, cement content, air content, and water-cement ratio.

The most significant test results available from this investigation are those relating concrete freeze-thaw durability and air void parameters.

It was found that air entrainment up to approximately six per cent air by volume improved the concrete freeze-thaw durability, by decreasing the air void size and spacing, and increasing the specific surface of the voids. At air contents greater than approximately six per cent, further air entrainment did not significantly improve the freeze-thaw durability.

Freeze-thaw durability was found to be practically independent of both cement content and water-cement ratio, for air contents above approximately two per cent. Protection of concrete from freeze-thaw deterioration is thus more effectively realized by air entrainment, than by variations in cement content and/or water-cement ratio.

Observed data showed that relationships between concrete durability and both specific surface and spacing factor are non-linear. A rapid increase in durability with decreasing void spacing indicates a critical void spacing factor of approximately 0.005 inch, for conditions of these tests.

ACKNOWLEDGEMENTS

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GLOSSARY OF TERMS AND ABBREVIATIONS

USED THROUGHOUT THIS THESIS

GLOSSARY OF TERMS USED THROUGHOUT THIS THESIS
(After A.S.T.M. Standards, 1960)

Admixture - A material other than water, aggregates, and portland cement
(including air-entraining portland cement and portland blast-
furnace slag cement), that is used as an ingredient of concrete
and is added to the batch before or during its mixing.

Air Content - A - The proportional volume of air voids in concrete, expressed
as a percentage of the volume of the hardened concrete.

Air-Entraining Agent - An addition for hydraulic cement or an admixture
for concrete or mortar which causes air, usually in small quantity,
to be incorporated in the form of minute bubbles into the concrete
or mortar during mixing, usually to increase its workability and
frost resistance.

Air Void - A small space enclosed by the cement paste in concrete, and
occupied by air. This term does not refer to capillary or other
openings of submicroscopic dimensions, or to voids within
particles of aggregate. Air voids are almost invariably larger
than two microns in diameter. The term includes both "entrapped"
and "entrained" air voids.

Apparent Air Content - The amount of air in mortar or concrete, expressed
as a percentage of the volume of the hardened concrete. This
quantity is determined directly from air content determinations
on fresh concrete by the pressure air meter.

Chord Intercept of Voids - $\bar{l}$ - The average length of chord across the
cross-sections of the air voids intercepted by a line of micro-
scopic traverse, in inches.

Coarse Aggregate - Aggregate predominantly retained on the No. 4 (4760 micron) sieve.

Entrained Air Voids - Air voids resulting from air entrainment. These voids are typically of the order of 10 to 100 microns in diameter, and spherical or nearly so because of the hydrostatic pressure to which they are subjected by the surrounding paste of water, cement, and aggregate fines.

Entrapped Air Voids - Air voids normally present in intergranular spaces in the cement and aggregate. These voids characteristically are 1 mm. or more in diameter, and irregular in shape because the periphery of the void follows the contour of the surrounding aggregate particles.

Fine Aggregate - Aggregate passing the 3/8-inch sieve and almost entirely passing the No. 4 (4760 micron) sieve and predominantly retained on the No. 200 (74 micron) sieve.

Fineness Modulus - An empirical factor obtained by adding the total percentages of a sample of the aggregate retained on each of a specified series of sieves, and dividing the sum by 100.

Number of Voids per Inch - The number of air voids intercepted by a line of microscopical traverse, in number of air voids per inch of traverse.

Paste Content - p - The proportional volume of cement paste in concrete, expressed as a percentage of the volume of the hardened concrete, calculated as the simple summation of the proportional volumes of the cement and water included in the concrete mixture.

Spacing Factor of Voids - $\bar{L}$ - A useful index related to the maximum distance
of any point in the cement paste from the periphery of an air
void, in inches. The calculation of the spacing factor of the
air void system is based upon an assumption that all air voids
in the sample are equal-sized spheres arranged in a simple cubic
lattice throughout the cement paste.

Specific Surface of Voids - α - The surface area of the air voids in
hardened concrete, expressed as square inches per cubic inch of
air void volume.

Water-Cement Ratio - The ratio of the amount of water, exclusive only of
that amount absorbed by the aggregates, to the amount of cement
in a concrete mixture. The ratios variously stated are: (1) by
bulk volume of cement, (2) by absolute volume of cement, (3) by
weight, and (4) in terms of gallons of water per sack of cement.

Terms Related to Microscopic Examination of Hardened Concrete

Linear Traverse (Rosiwal) Method - Determination of the volumetric composition
of a solid by integrating the distance traversed across areas
of each component along a line or along regularly-spaced lines in
one or more planes intersecting a sample of the solid. As this
method is applied in A.S.T.M. recommended practice, only air voids
are distinguished from the remainder of the concrete. Finely-
ground sections of concrete are examined microscopically along a
series of regularly-spaced lines of traverse and the following
data are obtained: (1) total number of sections of air voids
intersected, (2) total distance traversed across sections of voids,
and (3) total distance traversed across the remainder of the concrete.

Point-Count Method - Determination of the volumetric composition of a
solid by observation of the frequency with which areas of each
component coincide with a regular system of points in one or
more planes intersecting a sample of the solid.

Modified Point-Count Method - The point-count method supplemented by a
determination of the frequency with which areas of each component
of a solid are intersected by regularly-spaced lines in one or
more planes intersecting a sample of the solid. As applied in
A.S.T.M. recommended practice, only air voids are distinguished
from the remainder of the concrete. Finely-ground sections of
concrete are examined microscopically along a series of regularly-
spaced lines of traverse and the following data are obtained:
(1) total number of sections of air voids intersected, and (2),
frequency with which regularly-spaced points on the line of traverse
are superimposed on sections of air voids.

Abbreviations

A.C.I. - American Concrete Institute

A.S.T.M. - American Society For Testing and Materials

P.C.A. - Portland Cement Association

CHAPTER 1

INTRODUCTION

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INTRODUCTION

Western Canada's severe winter climate - extreme temperature ranges,
cyclic freezing and thawing, and wetting and drying - result in forces
tending to disrupt hardened portland cement concrete. Although the evolution
of dilating pressures in freezing concrete and the role of air voids in
preventing concrete deterioration are not completely understood, the use
of air entrainment to improve freeze-thaw durability is well known.

Air entrainment of cement paste is known to greatly increase the
freeze-thaw durability of concrete. Although Powers (1945, 1949) presented
several hypotheses to explain the source and nature of dilating forces
arising in concrete during freezing, he concluded that the resistance to
movement of water through freezing concrete is the primary source of pressure.
Hence, Powers concluded that the degree of protection of concrete subject
to freezing depends on the distance between entrained air voids, rather
than the total volume of air voids, provided that the void volume is
sufficient to accomodate the volume increase accompanying the freezing of
water in the concrete.

As a result of Powers' work (1945, 1949), study of the air void
system of hardened concrete has become concentrated on the determination of
significant void parameters, the most common of which are spacing, surface
area, number, and average size.

On the basis of work done by Makowichuk (1963), there was an

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indication that some relationship existed between the air void parameters of air-entrained concrete; notably the spacing factor and the specific surface of the air bubbles; and the durability of the concrete under cyclic freezing and thawing. Based upon the limited data available from his work, Makowichuk (1963) showed the relationships between durability factor and both spacing factor and specific surface as being linear. The major objective of this investigation was to attempt to establish the pattern of these relationships over a larger range of air content.

In this investigation, air void parameters, as determined by the lineal traverse method of microscopic examination (A.S.T.M. C457 - 60T), were measured and related to freeze-thaw durability data obtained from tests performed in accordance with A.S.T.M. procedure C 290 - 57T. Compressive strength data were also obtained for all concrete mixes prepared.

Included in this thesis as theory fundamental to an understanding of relationships between freeze-thaw durability and air void characteristics, are sections dealing with the composition and structure of hardened concrete, theories of freeze-thaw deterioration of hardened concrete, and effects of air entrainment of concrete.

Analysis and classification of materials used in this study are included in Chapter 3, followed in Chapter 4 by an outline of the testing programs and procedures employed. Since most of the test procedures were in accordance with A.S.T.M. recommended methods, reference is made to these standard tests.

Test data are summarized in tabular and graphical form in Chapter 6, while Chapter 7 includes discussion, evaluation, and interpretation of the data obtained. In Chapter 8 are stated the most significant findings of

this investigation, with respect to freeze-thaw durability and air void parameters. Suggested topics for future research are also presented in Chapter 8.

CHAPTER 2

FREEZE-THAW DURABILITY OF HARDENED CONCRETE

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FREEZE-THAW DURABILITY OF HARDENED CONCRETE

2.1 Composition and Structure of Hardened Cement Paste

Hardened cement paste has been described by Powers (1958) as composed essentially of gel particles, among which are calcium hydroxide crystals and air voids. Although Powers (1958) assumed spherical gel particles (FIGURE 2.1b), experimental data have shown that the particles are, in fact, more likely fibrous or platy (FIGURE 2.1a).

Throughout the hardened cement paste are dispersed pores of two different orders of size; the larger "capillary pores" are characteristically between approximately 200 and 800 Angstrom units in diameter, depending on the original water-cement ratio. The "gel pores" are considerably smaller, approximately 20 to 40 Angstrom units in diameter according to Powers and Brownyard (1948).

The capillary pores are remnants of spaces originally filled with water, which after hydration are partially occupied with cement-water reaction product. The gel pore system results from the porosity of the reaction product.

In addition to the minute capillary and gel pore systems, hardened cement paste may be associated with a network of larger voids, including entrapped air, entrained air, and water pockets. Verbeck (1956) stated that such voids range in size from about 10 microns or less to 2 mm. or more in diameter; many are therefore visible to the naked eye.

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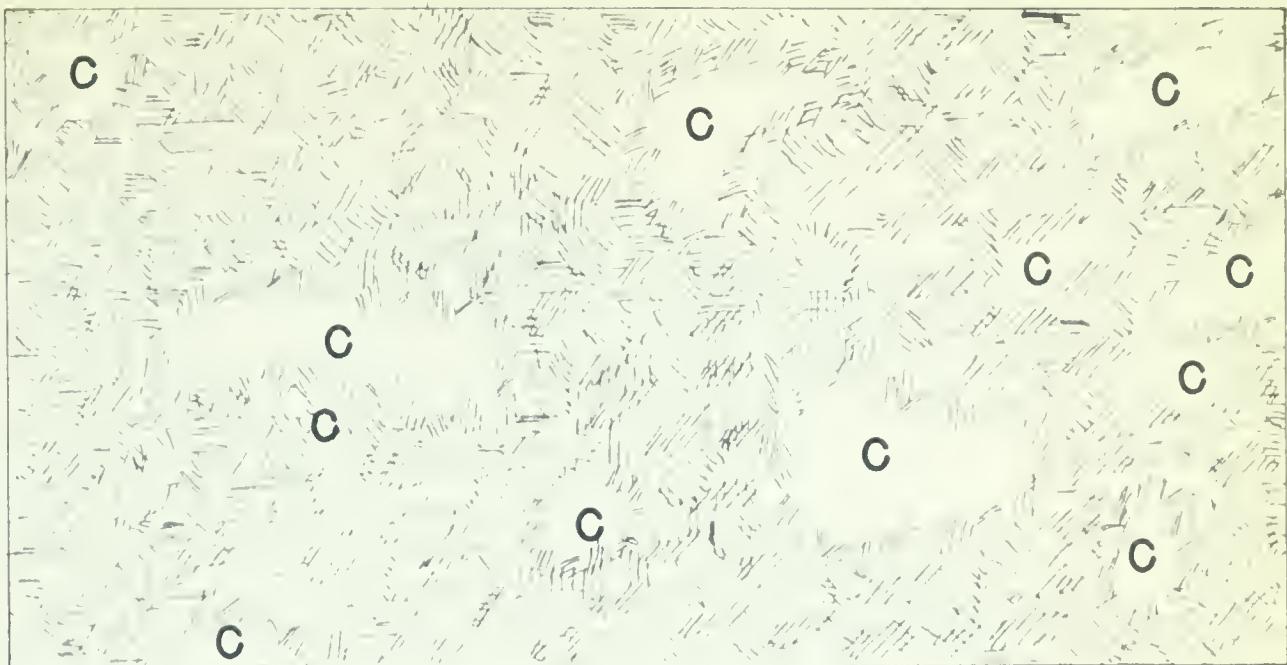
(a) Model of Paste Structure Based on Fibrous or Platy Gel Particles
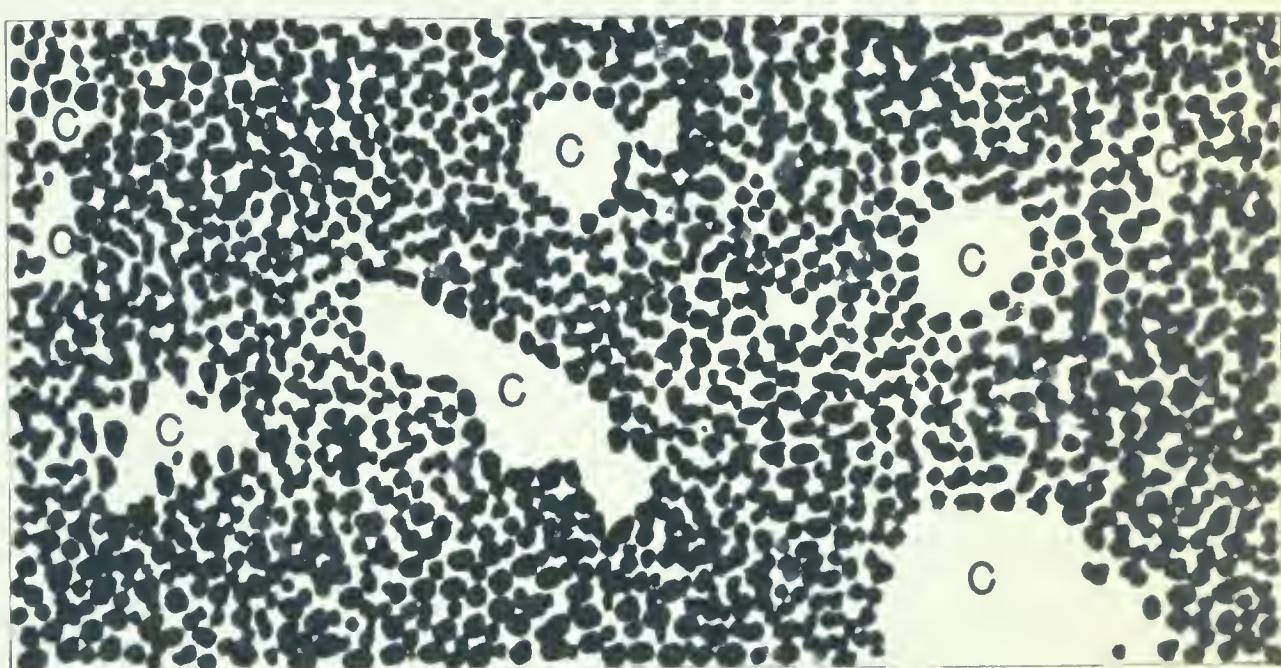
(b) Simplified Model of Paste Structure

Solid areas in (a) and (b) represent gel particles ; interstitial spaces are gel pores; capillary cavities are marked "c".

FIGURE 2.1 - Models of Structure of Hardened Cement Paste (After Powers, 1958)

Entrained air voids, of particular significance in this investig-
ation, range in size from a few microns to about 75 microns in diameter, and
are essentially isolated from each other (Lerch, 1960).

2.2 Void System of Concrete Aggregate

The void system of aggregate in hardened concrete is important
insofar as it reflects the ease with which the water within the aggregate
can be expelled into the surrounding cement paste, upon freezing.

Critical properties of the void system of concrete aggregate
include: (a) porosity, (b) pore size, and (c) the interconnection of
the voids.
In highly porous aggregates containing large interconnected voids, water
expulsion from the aggregate during freezing can be relatively easily
accomplished, and dilating pressures evolved are low.

2.3 Mechanisms of Freeze-Thaw Deterioration of Hardened Concrete

In hardened concrete exposed to freezing temperature, dilating
pressures develop in the hardened cement paste and/or in the concrete
aggregate.

Rational analyses of the behaviour of the two major components
of concrete (cement paste and aggregate) have been performed: analyses
of the action of hardened cement paste undergoing freezing have been developed
by Powers (1956), while Verbeck and Landgren (1960) have considered the
aggregate.

2.3.1 Analyses of Hardened Cement Paste During Freezing (Powers, 1956)

Case 1 - Hydraulic Pressure in a Closed Vessel

This analysis was based upon a consideration of minute individual
vessels having impermeable walls. The permeability of hardened cement paste

is sufficiently great to render this theory inapplicable to concrete.

Case 2 - Hydraulic Pressure in a Permeable Vessel

This theory is more applicable to concrete than is Case 1, since it considers vessels having permeable walls. Powers applied Case 2 to hardened concrete by considering a given capillary cavity as a vessel in which water can freeze. The presence in the capillary walls of gel pores duplicates the action of the prototype vessel, with walls having a very low coefficient of permeability.

Dilation of a permeable vessel containing a solution being frozen depends on the rate of water-volume production (by freezing), and the escape rate through the permeable walls. Powers applied Darcy's law to the flow of water through capillary walls, to obtain an expression for the maximum stress resulting in the vessel walls, viz

$$P_{max.} = \frac{0.09 \ w_f \ f(D)}{K \ A} \ \frac{dm}{dt} \ \ \ldots\ldots\ldots\ldots \ (1)$$

where: $P_{max.}$ = the maximum stress in the vessel walls, cm. of mercury,

w_f = the amount of freezible water in the vessel, cu. cm.,

A = inside area of the vessel, sq. cm.,

K = coefficient of permeability of the wall material, cm. per sec.,

f(D) = a function of wall thickness, cm.,

m = the fraction of total freezible water frozen, and

$\frac{dm}{dt}$ = the freezing rate of the water in the vessel, sec.$^{-1}$

Powers equated wall stresses produced by freezing, and the bursting strength of the vessel, to show that the critical wall thickness (i.e. the wall thickness whose bursting strength is equal to the pressures evolved in forcing water through it), is a function of wall permeability, freezing rate, and the strength of the vessel.

Although Powers quoted data of Valore (1950), and Powers and Helmuth (1953) substantiating the hydraulic pressure hypothesis of Case 2, certain phenomena were observed which could not be accounted for by this theory. In particular, the hydraulic pressure theory failed to explain prolonged dilation or contraction of concrete which was sometimes observed, at constant temperature. Powers' Case 3 provided the theory to account for these time-dependent phenomena.

Case 3 - Pressures Due to Osmosis or Ice Crystal Growth

Powers showed thermodynamically that water can migrate from an unfrozen region to a site of freezing, at a reduced temperature, until such time as thermodynamic equilibrium is re-established. Under the influence of free energy differentials, water flows from gel pores to the capillary cavities, until resulting pressure increases are sufficient to halt the flow.

The application of Case 3 to freezing concrete is thought to be limited, although Powers believed that ice crystal growth may be significant in mature concrete of high cement content.

2.3.2 Effect of Concrete Aggregate on Freeze-Thaw Durability of Hardened Concrete

Verbeck and Landgren (1960) studied the influence of the aggregate properties on the freeze-thaw durability of hardened concrete by analyzing the mechanisms of elastic accomodation, and the effects of cement paste

confinement and aggregate saturation.

When freezing of concrete occurs so quickly that water has no time to escape or be expelled from the aggregate within the concrete, the volume increase resulting from ice formation must be accomodated elastically within the aggregate. In most cases, however, freezing occurs slowly enough that water can, in fact, be expelled from the aggregate.

If the pore system of aggregate subject to freezing is only 91.7 per cent saturated, the unfilled voids are sufficient to accomodate the nine per cent expansion accompanying the formation of ice. Hydraulic pressures are not developed in such aggregates whose saturation is less than "critical", since no water need be expelled from the aggregate, during freezing.

If, however, the degree of saturation of the aggregate is greater than the critical value of 91.7 per cent, the volume increase resulting from freezing cannot be accomodated by the empty voids of the aggregate, and some water must be expelled. To prevent deterioration of the concrete, the cement paste surrounding the aggregate must be able to accomodate the water volume forced into it from the aggregate. Verbeck and Landgren (1960) showed that the thickness of the cement paste cover required for volumetric accomodation of water expelled from the aggregate during freezing is dependent upon aggregate porosity, aggregate particle size, and (inversely), upon the air content of the paste. Increased air content can significantly reduce the required expulsion distance (i.e. paste thickness), and hence can serve to moderate the vulnerability of unsound aggregate when used in air-entrained concrete.

2.3.3 The Taber-Collins Theory of Deterioration of Hardened Concrete

The Taber-Collins hypothesis is an application to concrete of the theory of ice lens formation which occurs in fine-grained soils. According to this theory, as the frost line advances, the water freezes. Ice lenses are formed in parallel sheets roughly perpendicular to the direction of the advancing frost line. The reduced vapour pressure resulting from freezing tends to draw water from the warmer inner regions to the ice lens, which grows until some disruption of the material occurs.

Powers (1956) conceded the possible application of the Taber-Collins hypothesis to fresh concrete, or to concretes of very high (i.e. greater than 0.8 by weight), water-cement ratio. However, most hardened, well-cured concrete has such low permeability (Powers, Copeland, Hayes, and Mann, 1954), that the quantity of water which can flow and form ice lenses is too small to disrupt the concrete. The Taber-Collins theory is therefore considered generally inapplicable to most concrete (Powers, 1956).

2.4 Evaluation of Freeze-Thaw Durability of Hardened Concrete

Two major considerations are involved in any method of laboratory evaluation of freeze-thaw durability of hardened concrete.

First, there must be a test method available which can measure deterioration of the concrete. Test methods used include loss in compressive strength, loss in weight, reduction in modulus of elasticity, expansion or contraction, and visual and microscopic examination (Troxell and Davis, 1956). Brewer (1948) believed that early indication of failure was most reliably shown by length change of the concrete. Swenson (1955) discounted the value of weight loss data, because of spalling and the effects of handling the concrete specimens.

The second problem involved in evaluation of the durability of concrete is the selection of proper exposure conditions, and the way in which they are to be incorporated into laboratory tests in order to duplicate realistically field conditions. In addition, it must be possible to relate laboratory test results to field conditions, so that concrete behaviour in use can be predicted.

2.4.1 Freeze-Thaw Testing of Hardened Concrete

There are presently four A.S.T.M. procedures in common use for evaluating the freeze-thaw durability of hardened concrete. The available methods are all accelerated tests, but involve different freezing rates and/or environments. The A.S.T.M. methods are summarized and discussed in TABLE 5.1 and section 5.2.3 of this report.

A.S.T.M. procedures involve the measurement of concrete deterioration under cyclic freeze-thaw testing by noting the decrease in dynamic modulus of elasticity, as measured by sonic apparatus. Terms are defined relating to freeze-thaw durability of the specimens, as follows:

if n = the fundamental transverse frequency at 0 cycles of freezing and thawing, and

n_1 = the fundamental transverse frequency after "c" cycles of freezing and thawing,

then P_c = the "relative dynamic modulus of elasticity" (per cent after "c" cycles of freezing and thawing)

$$= \frac{n_1^2}{n^2} \ \text{x} \ 100$$

Another term, the "durability factor" is defined by A.S.T.M. as follows:

$$\text{D.F.} = \text{"durability factor"}$$

$$= \frac{PN}{M}$$

where: P = relative dynamic modulus of elasticity at

N cycles, per cent,

N = the number of cycles at which P reaches the

specified minimum value for discontinuing the

test, or the specified number of cycles at

which the exposure is to be terminated,

whichever is less, and

M = the specified number of cycles at which the

exposure is to be terminated.

Semi-Rational Test Method of Powers (1955)

Powers (1955) suggested a procedure to determine the longest

soaking period, interspersed with occasional freezings, which a given sample

can withstand without "excessive" dilation. Dilation considered "excessive"

was taken by Powers to be 0.1 per cent length change. The soaking period

required for the concrete to attain this limiting dilation is then compared

to the interval over which the concrete is actually soaked, to predict

whether or not deterioration is likely to occur.

2.5 Prevention of Freeze-Thaw Deterioration of Hardened Concrete

By Air Entrainment

2.5.1 Action of Air-Entraining Agents - General

The use of air-entraining agents in even very small quantities

(0.01 to 0.05 per cent by weight of cement) results in the introduction

into the concrete of a larger amount of air than is present in the non-air-

entrained concrete. The entrained air bubbles are characteristically a few microns to about 75 microns in diameter, according to Lerch (1960).

The presence of these tiny air bubbles materially alters the properties of both the plastic mixture and the hardened concrete. Resulting beneficial properties of the plastic mix include an increase in workability and cohesiveness, and a reduction in segregation and bleeding tendency. These benefits all tend to produce a more homogeneous and durable concrete, and better looking structures. In the hardened concrete, air entrainment has the effect of increasing resistance to the aggressive action of sulfate water, and increasing freeze-thaw durability.

2.5.2 Effect of Air Entrainment on Strength of Concrete

Air entrainment tends to cause minor strength reductions in concrete, but such strength losses are usually more than offset by the beneficial effects of entrainment. Indeed, with lean mixes or small maximum size aggregate, air entrainment is accompanied by relatively large reductions in water requirement, and for these mixtures the strengths may even be increased (Lerch, 1960).

It is generally agreed (Klieger, 1952; Lerch, 1960), that the air content required to provide satisfactory durability will not result in serious strength loss in concrete of constant cement content, particularly if advantage is taken of the greater workability of the air-entrained concrete to reduce the sand and water content of the mixture.

2.5.3 Effect of Air Entrainment on Permeability of Concrete

Although the air content of concrete is increased by air entrainment, the entrained air is in the form of small, discontinuous voids which offer a

barrier to the passage of water. Air entrainment thus reduces the passage

of water through concrete (Lerch, 1960). Once air-entrained concrete has

dried, it is more resistant to the passage of water than regular concretes,

and will absorb less water, according to Lerch (1960).

In addition to the increased watertightness inherent in air-

entrained concrete, the greater uniformity due to improved workability of

the fresh concrete improves impermeability.

2.5.4 Effect of Air Entrainment on Freeze-Thaw Durability of Concrete

Air voids in concrete, whether entrapped air, entrained air,

or aggregate pores, are difficult to fill with water, since water cannot

spontaneously flow from a small capillary to a larger one. Powers (1946)

stated that a pressure exceeding one atmosphere is required to fill a

cavity under normal conditions, since air in the cavity becomes compressed

as the void is filled with water. Powers (1946) believed, however, that

pressures generated during freezing are probably more than sufficient to

fill such spaces.

It is generally thought, as a result of Powers' hydraulic pressure

theory of freeze-thaw deterioration of concrete (1945, 1949), that protection

from deterioration reflects the ability of a concrete's void system to

accomodate water and/or ice formed as freezing occurs.

Powers (1946) showed, however, that most concretes do, in fact,

contain sufficient air-filled space to accomodate expansion during freezing,

and yet they still deteriorate under cycles of freezing and thawing.

Powers concluded that, if the destructive action of freezing is due to

hydraulic pressure, the resistance to movement of water must be the primary

source of pressure, rather than dilation of concrete in an attempt to

accomodate ice formed as a result of freezing. Air voids represent points into which hydraulic pressure can be dissipated before becoming great enough to disrupt the concrete. Protection offered the concrete by air entrainment thus depends on the distance between the air voids, rather than the total volume of air present. Powers (1945) suggested a critical void spacing factor of about 0.01 inch in order for concrete to be able to withstand cyclic freezing and thawing. At higher freezing rates, however, the critical spacing factor may be as low as 0.005 inch, according to Powers (1955).

Concrete durability improvement is accomplished by the reduced void spacing factor resulting from air entrainment. If the quantity and distribution of air voids is such that the void spacing factor is, indeed, less than some critical value, the concrete will be durable under conditions of freezing and thawing.

CHAPTER 3

CLASSIFICATION AND ANALYSIS OF MATERIALS

CHAPTER 3

CLASSIFICATION AND ANALYSIS OF MATERIALS

3.1 Materials - General

The aggregates used in this investigation were supplied by Dales
Brothers Limited, from their Onoway source. The aggregates were delivered
in "coarse" (nominally 3/4-inch maximum size), and "fine" (smaller than
1/4-inch) size fractions, and were stored in separate bins prior to mixing.

The cement used was "Normal" (Type I) portland cement, supplied
by Inland Cement Company Limited, Edmonton. Prior to mixing, the cement
was stored in a metal container with a tight-fitting lid.

The air-entraining agent used in this investigation was "Darex".

3.2 Fine Aggregate

(i) Sieve Analysis (A.S.T.M. C 136 - 46)   (FIGURE 3.1)

Sieve	Per Cent Retained	Cumulative Per Cent Retained	Cumulative Per Cent Passing
#4	2.1	2.1	97.9
#8	9.9	12.0	88.0
#16	12.2	24.2	75.8
#30	10.6	34.8	65.2
#50	43.9	78.7	21.3
#100	17.8	96.5	3.5
Pan	3.5	100.0	0.0

Fineness Modulus = 2.48

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(ii) Specific Gravity and Absorption (A.S.T.M. C 128 - 59)

Test Number	Specific Gravity			Absorption
	Bulk (Oven-Dry)	Bulk (Sat'd. Surf.Dry)	Apparent	
1	2.51	2.55	2.62	1.53%
2	2.53	2.57	2.63	1.51%
Average	2.52	2.56	2.625	1.52%

(iii) Test For Organic Impurities (A.S.T.M. C 40 - 60)

Light Particles   =   0.032%

Color Test Number   =   #3

3.3 Coarse Aggregate

(i) Sieve Analysis (A.S.T.M. C 136 - 46)   (FIGURE 3.1)

Sieve	Per Cent Retained	Cumulative Per Cent Retained	Cumulative Per Cent Passing
1 in.	0	0	100
3/4 in.	0	0	100
1/2 in.	60.2	60.2	39.8
3/8 in.	20.3	80.5	19.5
1/4 in.	18.4	98.9	1.1
-1/4 in.	1.1	100.0	0

(ii) Specific Gravity and Absorption (A.S.T.M. C 127 - 59)

Test Number	Specific Gravity			Absorption
	Bulk (Oven-Dry)	Bulk (Sat'd. Surf. Dry)	Apparent	
1	2.56	2.58	2.63	1.12%
2	2.56	2.58	2.63	1.11%
Average	2.56	2.58	2.63	1.115%

(iii) Petrographic Analysis (A.S.T.M. C 40 - 60)

Quartz and Quartzite = 100%

(iv) Particle Shape Analysis

Angular = 98%

Sub-Angular = 2%

Total =100%

(v) Dry Rodded Unit Weight (A.S.T.M. C 29 - 60)

Test Number	Dry Rodded Unit Weight
1	96.60 lb./ cu. ft.
2	96.90 lb./ cu. ft.
Average	96.75 lb./ cu. ft.

(vi) Voids in Aggregate (A.S.T.M. C 30 - 37)

Per Cent Voids in Coarse Aggregate = 40%

3.4 Cement

(i) Time of Set by Vicat Needle (A.S.T.M. C 191 - 58)

Initial - hours:minutes - 2:47

Final - hours:minutes - 4:40

(ii) Compressive Strength of Mortar Cubes (A.S.T.M. C 109 - 58)

Age	Average Compressive Strength, p.s.i.
3 days	2750
7 days	3980
28 days	5730

(iii) Tensile Strength of Mortar (A.S.T.M. C 190 - 59)

Age	Average Tensile Strength, p.s.i.
3 days	480
7 days	570
28 days	605

(iv) Water For Normal Consistency (A.S.T.M. C 187 - 58)

Water For Normal Consistency   = 24.9%

(v) Chemical Analysis *

Loss on ignition   = 0.77%

SiO_2 = 21.20%

Al_2O_3 = 5.50%

Fe_2O_3 = 2.81%

CaO = 63.10%

MgO = 3.35%

Na_2O = 0.21%

K_2O = 0.81%

SO_3 = 2.21%

Free lime   = 1.17%

(vi) Fineness, Blaine *

Blaine Fineness   = 3007 sq. cm. per gm.

* Data supplied by Inland Cement Co. Ltd.
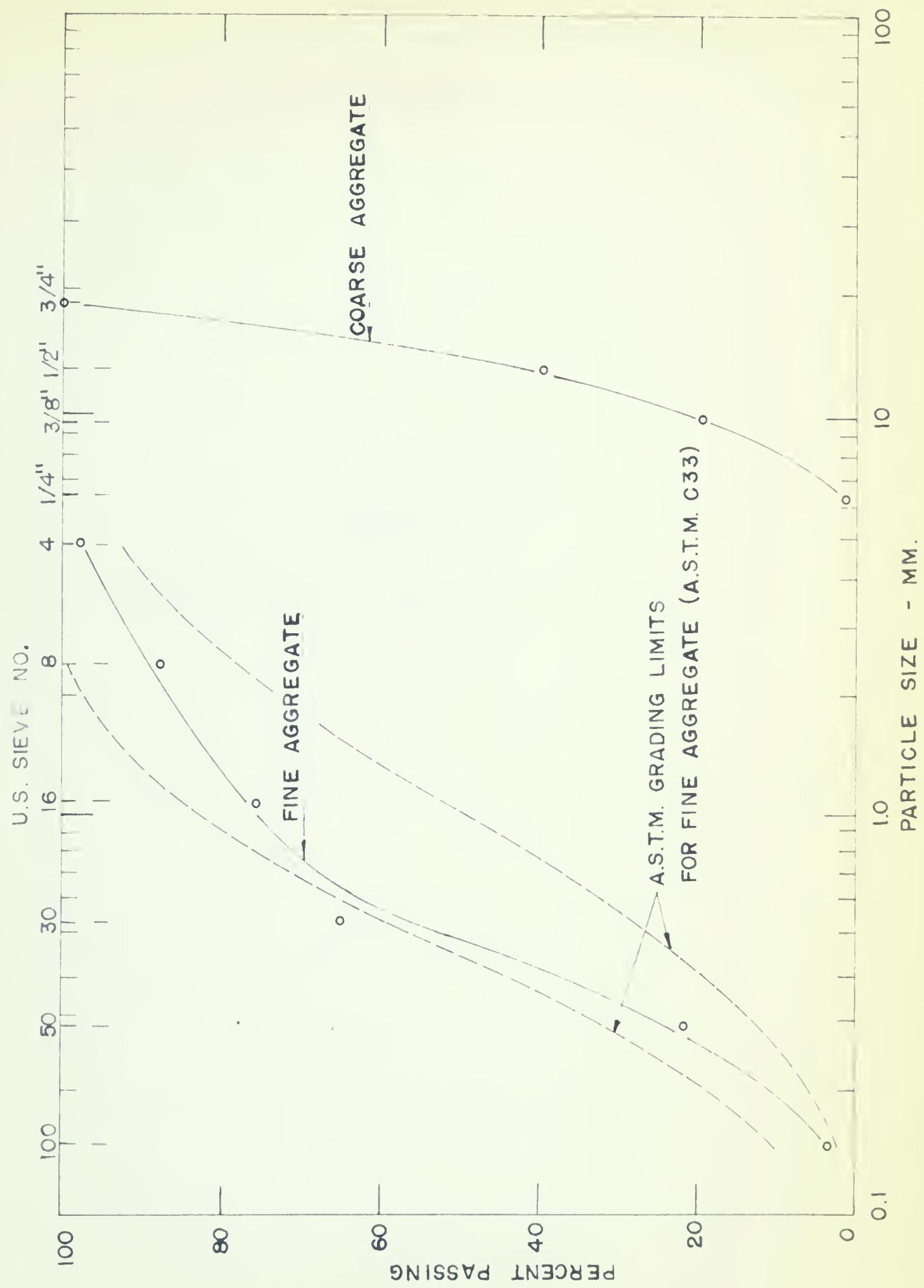
FIGURE 3.1 - Particle Size Distribution For the Aggregates Used
In This Investigation

CHAPTER 4

TESTING PROGRAM AND PROCEDURES - MIX DATA

CHAPTER 4

TESTING PROGRAM AND PROCEDURES - MIX DATA

4.1 General

Eighteen different concrete mixes were prepared for this investigation. These eighteen mixes represented six different air contents (from approximately 1.5 per cent to 9.0 per cent, by volume), and three cement contents (400, 550, and 700 pounds of cement per cubic yard).

The following components and procedures were kept constant throughout this investigation:

(a) fine and coarse aggregate type and grading,

(b) cement type and brand (Type I - "Normal"),

(c) type of air-entraining agent ("Darex"),

(d) consistency of fresh concrete as measured by the slump test (3 inches, plus or minus one-half inch),

(e) mixing conditions,

(f) casting equipment and procedures,

(g) curing conditions, and

(h) equipment and procedures for testing the cast specimens (compressive strength, freeze-thaw durability, and microscopic examination).

A.S.T.M. procedures were followed where possible, and reference is made to these standard methods of test.

4.2 Mix Designation

Since the two variables in the concrete mixes for this investigation were cement content and air content, both these were incorporated into the mix designation. Each mix was thus designated by its cement content and air content. For example, mix "400 - 1.6" refers to the mix whose cement content was 400 pounds per cubic yard, and whose air content was 1.6 per cent by volume, as measured using A.S.T.M. test procedure C 231.

4.3 Mix Design Methods

Mix design was performed in accordance with "A.C.I. Standard - Recommended Practice for Selecting Proportions for Concrete (A.C.I. 613 - 54). Cement contents selected (400, 550, and 700 pounds per cubic yard) were arbitrarily chosen to represent the range commonly used in practice.

Although the mix designs gave estimates of the mixing water requirements, the quantities of water actually used were adjusted during mixing to obtain the required slump of three inches, plus or minus one-half inch.

Mix design data are summarized in TABLES 4.1, 4.2, and 4.3.

4.4 Mixing

Prior to mixing, the mixer was "buttered" using a concrete batch similar to the first test mix.

The mixing procedure closely followed A.S.T.M. C 192 - 59, with the exception of the order in which the materials were added to the mixer.

In summary, the mixing sequence was as follows:

(a) the mixer was "buttered", and then emptied,

(b) the materials were batched, in the order; (i) coarse aggregate,

(ii) water, (iii) cement, (iv) fine aggregate, and

(v) air-entraining agent,

(c) the materials were mixed approximately three minutes,

(d) the fresh concrete was allowed to stand in the mixer for approximately three minutes, during which time the slump was checked,

(e) the materials were mixed for another two minutes, during which time the water content was adjusted as necessary, and

(f) the air content was measured, using a commercial air meter.

4.5 Casting

The following specimens were made from each concrete mix:

(a) twenty cylinders (three inches in diameter by six inches long), and

(b) three beams (3 - 1/2 inches by 4 - 1/2 inches by 16 inches).

The cylindrical specimens were cast in waxed cardboard molds. The concrete was placed into the molds in two approximately-equal layers, and external vibration was applied for a total time of approximately 20 seconds per sample, to compact the fresh concrete.

The beam specimens were cast in thinly-greased metal molds. Concrete was placed into the molds in two approximately-equal layers, and external vibration was applied for a total time of approximately 20 seconds.

All molds were slightly overfilled after compaction, and were then struck off level with a trowel.

4.6 Curing

Immediately after casting, the specimens were removed to a table

and covered with polyethylene to prevent surface drying. The specimens

were removed from the molds approximately 24 hours after casting, and

placed in a curing tank containing a saturated lime solution, in accordance

with A.S.T.M. C 192 - 59. The curing tank was kept in a room whose temperature

was thermostatically controlled. Although small temperature fluctuations

undoubtedly occurred during curing of the specimens, the average temperature

was close to that required by A.S.T.M. C 192 - 59 (73.4°F.).

4.7 Testing the Cast Concrete Specimens

4.7.1 Compressive Strength Testing

Prior to compressive strength testing, the cylindrical specimens

were capped with a sulfur-fire clay mixture.

Of the twenty cylinders made from each concrete mix, four were

tested at ages of 7 days, 14 days, and 28 days, and the remainder were

stored for testing at ages of three and six months. Time limitations pre-

vented the inclusion of test data from these greater ages in this report.

Compressive strength testing was performed in accordance with

A.S.T.M. C 39 - 59. Loading was maintained at 35 p.s.i. per second, by

means of a load pacer on a Baldwin hydraulic testing machine.

4.7.2 Freeze-Thaw Testing

After curing for one day in air and 13 days in saturated lime

solution at room temperature, two beams of each mix were selected for

freeze-thaw testing.

Before beginning freeze-thaw testing, the weights and original

fundamental transverse frequencies of the beams were measured and recorded.

The beams were then placed in individual containers in the freeze-thaw bath, covered with water, and subjected to two-hour cycles of freezing and thawing, in accordance with A.S.T.M. C 290 - 57T. At intervals of approximately two days, the freeze-thaw process was halted, the beams were removed, dried, and their fundamental transverse frequencies were again measured.

The beams were inverted before being returned to the bath. In order to minimize differential effects due to temperature variation throughout the bath, the beams were also regularly moved about in the bath.

At the end of the freeze-thaw testing (i.e. after 300 cycles, or when the "relative dynamic modulus" was reduced to 60 per cent of its original value), the beams were removed from the bath, dried, and weighed.

4.7.3 Microscopic Examination

A longitudinal slice of concrete approximately one inch thick was cut from the center of one beam of each mix, for microscopic examination.

A surface of the concrete slice was prepared as recommended by A.S.T.M. C 457.

Microscopic examination of the prepared surfaces was performed in accordance with the lineal traverse method described in A.S.T.M. C 457 - 60T.

4.8 Summary of Test Procedures Used in This Investigation

4.8.1 Aggregate Tests

	A.S.T.M. Designation
Unit Weight of Aggregate	C 29 - 60
Voids in Aggregate for Concrete	C 30 - 37
Organic Impurities in Sands for Concrete	C 40 - 60

Specific Gravity and Absorption of

Coarse Aggregate   C 127 - 59

Specific Gravity and Absorption of

Fine Aggregate   C 128 - 59

Sieve Analysis of Fine and Coarse

Aggregate   C 136 - 46

Recommended Practice for Petrographic

Examination of Aggregates for Concrete   C 295 - 54

4.8.2 Cement Tests   A.S.T.M. Designation

Compressive Strength of Portland

Cement   C 109 - 58

A.S.T.M. Procedures for Portland

Cement   C 150 - 60

Tensile Strength of Portland Cement   C 190 - 59

Time of Setting by Vicat Needle   C 191 - 58

4.8.3 Concrete Tests   A.S.T.M. Designation

Slump of Portland Cement Concrete   C 143 - 58

Concrete Compression and Flexure Test

Specimens, Making and Curing in the

Laboratory   C 192 - 59

Fundamental Transverse, Longitudinal and

Transverse Frequencies of Concrete Specimens C 215 - 60

Freezing and Thawing in Water, Rapid,

Resistance of Concrete Specimens to   C 290 - 57T

Air-Void Content, Specific Surface, and

Spacing Factor of the Air-Void System of

Hardened Concrete, Microscopical

Determination of   C 457 - 60T

4.9 Mix Data

TABLE 4.1

MIX DESIGN PROPORTIONS PER CUBIC YARD

(SATURATED SURFACE-DRY BASIS)

MIX	DATE CAST	DESIGN MIX PROPORTIONS (SATURATED SURFACE-DRY)				
		CEMENT lbs.	WATER lbs.	COARSE AGG. lbs.	FINE AGG. lbs.	DAREX cc.
400 - 1.6	24 June, '63	400	340	1670	1465	--
550 - 1.4	24 June, '63	550	340	1670	1340	--
700 - 1.3	24 June, '63	700	340	1670	1220	--
400 - 2.8	25 June, '63	400	340	1670	1380	27.4
550 - 2.9	25 June, '63	550	340	1670	1260	37.4
700 - 3.0	25 June, '63	700	340	1670	1135	47.9
400 - 4.1	18 July, '63	400	320	1670	1345	54.8
550 - 3.4	18 July, '63	550	320	1670	1220	74.8
700 - 3.3	18 July, '63	700	320	1670	1100	95.8
400 - 6.3	19 July, '63	400	298	1670	1315	109.6
550 - 6.0	19 July, '63	550	298	1670	1190	149.6
700 - 6.3	19 July, '63	700	298	1670	1070	191.6
400 - 8.9	12 Aug.,'63	400	278	1670	1280	164.4
550 - 8.2	12 Aug.,'63	550	278	1670	1150	224.4
700 - 7.9	12 Aug.,'63	700	278	1670	1040	287.4
400 - 8.7	13 Aug.,'63	400	258	1670	1240	219.2
550 - 9.0	13 Aug.,'63	550	258	1670	1120	299.2
700 - 8.8	13 Aug.,'63	700	258	1670	1000	383.2

TABLE 4.2

ACTUAL MIX PROPORTIONS FOR TWO CUBIC FEET

MIX	CEMENT lbs.	AGGREGATE (BIN CONDITION)		WATER ADDED lbs.	WATER IN AGG.		TOTAL WATER lbs.	NET WATER-CEMENT RATIO
		COARSE lbs.	FINE lbs.		C.AGG. lbs.	F.AGG. lbs.		
400 - 1.6	29.7	122.8	110.9	24.3	-1.1	+2.1	25.3	0.853
550 - 1.4	40.8	122.8	101.5	22.0	-1.1	+2.0	22.9	0.561
700 - 1.3	52.0	122.8	92.5	21.5	-1.1	+1.8	22.2	0.427
400 - 2.8	29.7	122.8	104.5	20.9	-1.1	+2.0	21.8	0.734
550 - 2.9	40.8	122.8	95.4	21.6	-1.1	+1.8	22.3	0.546
700 - 3.0	52.0	122.8	85.8	21.0	-1.1	+1.7	21.6	0.415
400 - 4.1	29.7	122.8	102.0	20.6	-1.1	+2.0	21.5	0.724
550 - 3.4	40.8	122.8	92.2	19.6	-1.1	+1.8	20.3	0.498
700 - 3.3	52.0	122.8	83.5	19.5	-1.1	+1.6	20.0	0.385
400 - 6.3	29.7	122.8	99.6	17.6	-1.1	+1.9	18.4	0.620
550 - 6.0	40.8	122.8	90.2	18.7	-1.1	+1.7	19.3	0.473
700 - 6.3	52.0	122.8	81.2	19.9	-1.1	+1.6	20.4	0.392
400 - 8.9	29.7	122.8	97.0	17.3	-1.1	+1.9	18.1	0.610
550 - 9.2	40.8	122.8	87.1	18.8	-1.1	+1.7	19.4	0.476
700 - 7.9	52.0	122.8	78.8	20.8	-1.1	+1.5	21.2	0.408
400 - 8.7	29.7	122.8	94.0	17.5	-1.1	+1.8	18.2	0.613
550 - 9.0	40.8	122.8	85.0	19.6	-1.1	+1.6	20.1	0.493
700 - 8.8	52.0	122.8	75.7	21.3	-1.1	+1.5	21.7	0.417

TABLE 4.3

MIX QUANTITIES - WEIGHTS AND VOLUMES

(Weights in Brackets)

MIX	QUANTITIES Weights in lbs., Volumes in cu. ft.						TOTAL VOLUME	PASTE CONTENT
	CEMENT	WATER	CEMENT+WATER	FINE AGG.	C.AGG.	AIR	cu.ft.	
400 - 1.6	(29.7) 0.151	(25.3) 0.405	0.556	(110.9) 0.693	(122.8) 0.760	0.033	2.041	0.272
550 - 1.4	(40.8) 0.208	(22.9) 0.367	0.575	(101.5) 0.635	(122.8) 0.760	0.030	2.000	0.288
700 - 1.3	(52.0) 0.265	(22.2) 0.355	0.620	(92.5) 0.578	(122.8) 0.760	0.027	1.985	0.312
400 - 2.8	(29.7) 0.151	(21.8) 0.347	0.498	(104.5) 0.654	(122.8) 0.760	0.058	1.970	0.252
550 - 2.9	(40.8) 0.208	(22.3) 0.357	0.565	(95.4) 0.596	(122.8) 0.760	0.057	1.978	0.285
700 - 3.0	(52.0) 0.265	(21.6) 0.345	0.610	(85.8) 0.536	(122.8) 0.760	0.059	1.965	0.310
400 - 4.1	(29.7) 0.151	(21.5) 0.344	0.495	(102.0) 0.637	(122.8) 0.760	0.083	1.975	0.250
550 - 3.4	(40.8) 0.208	(20.3) 0.325	0.533	(92.2) 0.576	(122.8) 0.760	0.065	1.934	0.276
700 - 3.3	(52.0) 0.265	(20.0) 0.320	0.585	(83.5) 0.522	(122.8) 0.760	0.063	1.930	0.302
400 - 6.3	(29.7) 0.151	(18.4) 0.295	0.446	(99.6) 0.622	(122.8) 0.760	0.121	1.949	0.228
550 - 6.0	(40.8) 0.208	(19.3) 0.309	0.517	(90.2) 0.564	(122.8) 0.760	0.119	1.960	0.263
700 - 6.3	(52.0) 0.265	(20.4) 0.327	0.592	(81.2) 0.507	(122.8) 0.760	0.123	1.982	0.299

TABLE 4.3 - cont'd.

MIX	QUANTITIES Weights in lbs., Volumes in cu. ft.						TOTAL	PASTE CONTENT
	CEMENT	WATER	CEMENT+WATER	FINE AGG.	C.AGG.	AIR		
400 - 8.9	(29.7) 0.151	(18.1) 0.290	0.441	(97.0) 0.606	(122.8) 0.760	0.178	1.985	0.221
550 - 8.2	(40.8) 0.208	(19.4) 0.310	0.518	(87.1) 0.544	(122.8) 0.760	0.163	1.985	0.260
700 - 7.9	(52.0) 0.265	(21.2) 0.339	0.604	(78.8) 0.493	(122.8) 0.760	0.158	2.015	0.300
400 - 8.7	(29.7) 0.151	(18.2) 0.291	0.442	(94.0) 0.588	(122.8) 0.760	0.170	1.960	0.225
550 - 9.0	(40.8) 0.208	(20.1) 0.321	0.529	(85.0) 0.531	(122.8) 0.760	0.180	2.000	0.264
700 - 8.8	(52.0) 0.265	(21.7) 0.347	0.612	(75.7) 0.473	(122.8) 0.760	0.176	2.021	0.302

CHAPTER 5

DISCUSSION OF APPARATUS AND PROCEDURES

CHAPTER 5

DISCUSSION OF APPARATUS AND PROCEDURES

5.1 Discussion of Apparatus

5.1.1 General

Apparatus used throughout this investigation for freeze-thaw
testing and microscopic examination of concrete was previously employed and
described by Lauer (1948), and Makowichuk (1963). It is therefore unnecessary
to repeat descriptions of the test equipment employed, other than to emphasize
significant features of the apparatus.

Mixing, curing, and capping equipment was standard in all respects,
and so is not considered in this discussion.

5.1.2 Apparatus - Compressive Strength Testing

Compressive strength testing was performed using a hydraulic
Baldwin Southwark-Emery machine. The machine has a total capacity of 300,000
pounds, but a lower load range of 0 to 50,000 pounds was employed throughout
this testing program.

A load pacer was used to control the loading rate at 35 p.s.i.
per second, in accordance with A.S.T.M. C 192, which specifies that loading
be applied at a rate between 20 and 50 p.s.i. per second.

5.1.3 Apparatus - Freeze-Thaw Durability Testing

Significant components of the freeze-thaw apparatus include a
specimen tank, a hot tank, and a cold tank. The control system is set to
two-hour cycles of freezing and thawing within the specimen tank.

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The temperatures during one freeze-thaw cycle range from 40° F. to 0° F.: the cycle consists of a one-hour heating cycle (from 0°F. to 40°F.), and a one-hour freezing cycle (from 40°F. to 0°F.).

Within the specimen tank are twelve individual containers to hold concrete beam samples 3-1/2 inches by 4-1/2 inches by 16 inches, in a vertical position.

The effects of temperature variations throughout the bath were minimized during testing by regularly inverting the concrete specimens, and changing their positions within the bath.

5.1.4 Apparatus - Microscopic Examination

Significant components of the apparatus used for microscopic examination are a stage or platform, a mounted microscope, a sample illuminator, and lead screws by which the stage can be moved.

The lead screws are such that traverse lengths of voids and hardened concrete can be separately recorded. Another lead screw is used to move the specimen vertically, prior to beginning another traverse.

The magnification of the microscope is an important variable in microscopic examination. In this investigation, a binocular microscope of magnification 90x was used. Brown and Pierson (1951) suggest a magnification of 30x to 40x for examination of polished concrete sections, but observations from this investigation indicate that resolving power at such magnification would be low. The importance of magnification, resolving power, etc. is further treated under "Discussion of Procedures".

The sample illuminator was adjusted to give light incident at a low (approximately 20 degrees) angle to the polished concrete surface being examined.

5.2 Discussion of Procedures

5.2.1 General

A.S.T.M. test procedures were used where possible throughout this investigation, so reference is made to these standard methods. Significant features and inadequacies of the available test methods are discussed in this chapter.

5.2.2 Procedures - Compressive Strength Testing

Compressive strength testing during this study was entirely in accordance with recommended A.S.T.M. procedures.

It is significant to note that compressive strengths reported in this thesis refer to average values obtained from tests on cylindrical specimens three inches in diameter and six inches long. Troxell and Davis (1956) stated that compressive strength values obtained from such specimens are approximately 106 per cent of those which could be expected from cylinders of the same concrete 6 inches in diameter, and 12 inches long.

5.2.3 Procedures - Freeze-Thaw Durability Testing

A prerequisite of any laboratory test procedure is that conditions of the test duplicate those to which the material is actually subjected in use. Laboratory freeze-thaw testing differs markedly from field exposure conditions in two important respects; the rate of freezing, and the length of continuous exposure to water.

(i) Effect of Freezing Rate

TABLE 5.1 shows the freezing rates to which concrete specimens are exposed in common A.S.T.M. test methods used to evaluate freeze-thaw durability.

TABLE 5.1

DETAILS OF A.S.T.M. FREEZING AND THAWING TESTS

A.S.T.M. Test Designation	Temp. Range, °F.	Average Cooling Rates, °F. per hour.	
		Min. Average	Max. Average
C 290 - 57T	0 to 40	13.3	b
C 291 - 57T	0 to 40	13.3	b
C 292 - 57T	0 to 73.4	3.1	4.1
C 310 - 57T	0 to 40	5.7	8.0

b - center and surface temperatures not
to differ by more than 50° F.

According to Powers (1951), field measurements indicate that

concrete pavements seldom cool faster than 5° F. per hour. The freezing

rates quoted in TABLE 5.1 for test procedures C 290 and C 291 are seen to

be considerably greater than those to which the concrete is actually subjected

in use. Accelerated laboratory freezing rates were thought to be means of

speeding up the normally time-consuming deterioration of concrete due to

freezing. In actual fact, however, the accelerated freezing rates distort

freeze-thaw behaviour of concrete. As well as overall distortion of concrete

behaviour, various concretes are affected relatively differently by high

freezing rates. Powers (1955), for example, quoted data which show that

both plain and air-entrained concretes may be equally protected from

deterioration at low freezing rates: at higher freezing rates, however,

air-entrained concrete is much better protected than non-entrained paste.

The influence of freezing rate on concrete durability depends on

the mechanisms responsible for the dilating pressure in the concrete, since the evolution of dilating pressures is time-dependent. Powers (1945, 1949) believed, for example, that dilating pressures in rock particles and cement pastes of ordinary quality are hydraulic in nature, while those in dense pastes (low water-cement ratio, well-cured) are due to ice crystal growth and osmotic pressures. The latter two mechanisms require time for evolution, so that fast freezing minimizes their importance. Conversely, hydraulic pressures tend to build up quickly, and then dissipate with time, so that fast freezing maximizes concrete damage due to hydraulic pressure.

The effect of freezing rate on required protection (by air entrainment) is considerable: Powers (1955) summarized data which showed that, at a certain freezing rate, the void spacing factor required to hold the rate of deterioration below a critical value was about 0.005 inch; at a lower freezing rate, however, the critical void spacing factor was raised to twice the former value, 0.01 inch.

In this investigation, it could be expected that the high freezing rate of A.S.T.M. procedure C 290 - 57T resulted in critical void spacing values less than those which would be required for protection during actual freezing in use (i.e., at lower freezing rates). The decreased critical spacing factor estimated from rapid freezing tests thus causes an overestimate of the air entrainment required for adequate concrete protection.

(ii) Effect of Exposure to Moisture

Common A.S.T.M. freeze-thaw test procedures require continuous exposure of concrete specimens to water during testing. In fact, however, most concrete has intermittent drying periods during which time it can recover from the effects of soaking. Continuous laboratory exposure of

concrete to water thus imposes more severe conditions on concrete than are likely to be experienced in use. The severe exposure conditions are likely to result in an overestimate of air requirements for a concrete to be adequately protected, upon freezing.

In the freezing of rich concrete mixes osmotic pressure development becomes significant according to Powers (1956). Under rapid freezing rates used in the accelerated laboratory freeze-thaw tests, it may be possible that osmotic pressure cannot fully develop in the available time. In such instances, accelerated freezing can result in an underestimate of the air required to protect the concrete.

(iii) Effect of Age at Start of Freeze-Thaw Testing

The effect of concrete age on freeze-thaw test results is important only insofar as it influences the strength attained by the concrete when freezing begins, and dilating pressures develop. Relative magnitudes of the concrete strength and dilating pressure dictate whether or not deterioration of the concrete actually occurs.

All freeze-thaw testing for this investigation was in accordance with A.S.T.M. C 290 - 57T, which requires that cyclic freezing and thawing be started when the concrete is 14 days old. The rate at which strength development occurs in the concrete is seen (TABLES 6.2 and 6.3) to be variable, and so it is to be expected that behaviour of freezing concrete will be variable, for a constant magnitude of dilating pressure.

Although the significance of concrete age on its freeze-thaw durability is apparent, the importance of age is known only in a qualitative way.

Powers (1962) suggested the use of a "Maturity Factor" to predict

the age at which green concrete has sufficient strength to withstand

dilating pressures arising from freezing. He showed that the necessary

prehardening time is a function of cement characteristics, water-cement

ratio, and curing temperature.

The analysis of Powers (1962) is significant since it recognized

the importance of certain concrete properties, as well as the severity

of the freezing conditions imposed upon the concrete.

(iv) Measurement of Freeze-Thaw Deterioration of Concrete by

Sonic Methods

It is assumed throughout freeze-thaw testing that sonic measure-

ments can, indeed, determine concrete deterioration. The significance and

value of sonic measurements in durability evaluation is beyond the scope

of this thesis. However, a consideration of the physical details of the

apparatus and procedures permits the following observations to be made:

(a) Surface dirt and moisture probably affect the contact between

the specimen, supports, and/or probe used, resulting in

erratic observations.

(b) The state of the concrete immediately in contact with the

probe affects observed data.

(c) The electronic equipment for supplying an input frequency

and measuring the resulting resonant frequency is undoubtedly

more delicate than most equipment used in concrete testing.

The electronic equipment itself might be the cause of some

distortion of test data.

(d) In this investigation, the decrease in dynamic modulus of

elasticity of concrete specimens undergoing freeze-thaw testing

was attributed entirely to the decreased continuity of the

hardened concrete mass.

In fact, however, reductions in the dynamic modulus can also occur as a result of changes in geometry and/or weight of the specimen tested.

Weight loss data were obtained for the freeze-thaw specimens tested (TABLE 6.5), but no attempt was made to evaluate the effect of weight loss on the reduction of the modulus of elasticity.

In an attempt to achieve uniformity of sonic measurements, each specimen was surface dried and cleaned before testing. Measurements of resonant frequency were repeated with the concrete specimen slightly shifted from its original position, to prevent placement of the probe affecting results. The beam was also inverted, and its resonant frequency re-measured, as a check on the initial measurements.

5.2.4 Procedure - Microscopic Examination

(i) General

Although the principles of microscopic examination are essentially simple, there are some practical aspects of the procedures which complicate the test methods.

(ii) Necessity of Obtaining a Good Polished Surface

The required quality of a prepared polished concrete surface is dictated by the ability of an examiner to quickly and easily study the surface. The requirements of the surface to be examined are therefore dependent to some extent upon the equipment being used for examination (i.e. power and resolving power of the microscope, lighting, etc.), and the requirements of the examiner.

During this investigation, polishing with the coarsest grinding powder was continued until all saw marks were removed from the surface being prepared. Grinding with succesively-finer compounds then proceeded until all traces of previous grinding were removed. In order to prevent scratching of a surface, it was carefully washed of all traces of a particular grinding powder before a finer powder was used.

As the air content of the concrete was increased, surface preparation became increasingly difficult. With high air contents, the large number of air voids in the cement paste resulted in a crumbly mass which was easily broken down during surface preparation. The use of carnauba wax to impregnate the concrete surface undoubtedly minimized crumbling of the paste during grinding, by supporting the thin septa and ridges between air voids. The value of the wax was particularly pronounced during the preparation of surfaces of concrete whose air content was above approximately six per cent.

(iii) Magnification and Resolving Power of Microscope

The magnification of the microscope used during study of polished sections in this study was 90x, considerably higher than the 30x to 40x suggested by Brown and Pierson (1951). Two conflicting requirements of microscopes used for study of sections are that: (a) the magnification must be sufficiently high to allow accurate detection and measurement of minute air voids, and (b) magnification must not be so high that microscopic examination becomes excessively time-consuming.

Experience gained in this investigation suggests that magnification of 30x to 40x might be too low to permit positive identification and measurement of air voids encountered. A.S.T.M. procedures offer considerable latitude in the choice of magnification, by allowing the use of from 30 to 125 power.

The use of a binocular microscope and light incident at a low angle (approximately 20 degrees) to the polished surface greatly facilitated identification of the components of the hardened concrete. Had a binocular microscope and incident light not been used, considerable difficulty would have been experienced in differentiating between air voids, gouged areas, and clear mineral crystals in the concrete.

(iv) Differentiation Between Voids

As discussed in Chapter 2, there are macropores (i.e. water and entrapped air voids) in hardened cement paste, as well as entrained air. Although these macropores are large in size, they are so widely spaced that they are inefficient as sources of pressure relief during freezing of concrete, and so contribute little to the freeze-thaw durability of the hardened mass.

It was decided to neglect entrapped air and water voids during microscopic examination in this study: only entrained air voids were counted and measured during microscopic analysis. The distinction between entrained air voids and the macropores was arbitrary, but was generally based on differences in size and/or shape, since the entrained air voids are characteristically spherical, and the macropores are irregular (and larger).

(v) Traverse Length Required For Adequate Sample

Minimum traverse lengths for various maximum size aggregates are suggested by A.S.T.M., based on statistical sampling requirements. Suggested minimum linear traverse lengths range from 160 inches for 6-inch maximum aggregate, to 55 inches for 3/16-inch maximum size aggregate. With the 3/4-inch aggregate used in this investigation, A.S.T.M. standards suggest a minimum traverse length of 90 inches, a requirement which was exceeded in all microscopic examinations performed in this study.

CHAPTER 6

TEST RESULTS

CHAPTER 6

TEST RESULTS

6.1 Compressive Strength Test Results

TABLE 6.1

COMPRESSIVE STRENGTH SUMMARY

MIX	WATER-CEMENT RATIO BY WEIGHT	VOIDS-CEMENT RATIO BY VOLUME	AVERAGE COMPRESSIVE STRENGTH AT VARIOUS AGES, p.s.i.		
			7 Days	14 Days	28 Days
400 - 1.6	0.853	2.96	1420	2100	2710
550 - 1.4	0.561	1.95	2800	3660	4630
700 - 1.3	0.427	1.47	5110	5650	6290
400 - 2.8	0.734	2.72	1600	2160	2790
550 - 2.9	0.546	2.02	3230	3870	4470
700 - 3.0	0.415	1.55	4430	4880	5430
400 - 4.1	0.724	2.87	1720	2230	2950
550 - 3.4	0.498	1.92	2990	3570	4480
700 - 3.3	0.385	1.48	3980	4510	5190
400 - 6.3	0.620	2.82	1405	1790	2130
550 - 6.0	0.473	2.08	2090	2700	3320
700 - 6.3	0.392	1.73	3020	3620	4280
400 - 8.9	0.610	3.14	1110	1450	1670
550 - 8.2	0.476	2.31	1930	2320	2550
700 - 7.9	0.408	1.91	2550	2950	3300
400 - 8.7	0.613	3.11	1070	1450	1640
550 - 9.0	0.493	2.45	1760	2110	2360
700 - 8.8	0.417	2.01	2870	2880	3110

TABLE 6.2

RELATIVE COMPRESSIVE STRENGTHS AT VARIOUS AGES

MIX	AVERAGE COMPRESSIVE STRENGTH AT AGE SHOWN, p.s.i.			RELATIVE COMPRESSIVE STRENGTH AT VARIOUS AGES, AS PER CENT OF 28-DAY COMPRESSIVE STRENGTH		
	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
400 - 1.6	1420	2100	2710	52.4	77.5	100
550 - 1.4	2800	3660	4630	60.6	79.3	100
700 - 1.3	5110	5650	6290	81.3	89.8	100
400 - 2.8	1600	2160	2790	57.4	77.4	100
550 - 2.9	3230	3870	4470	72.4	86.5	100
700 - 3.0	4430	4880	5430	81.5	89.8	100
400 - 4.1	1720	2230	2950	58.3	75.6	100
550 - 3.4	2990	3570	4480	66.8	79.8	100
700 - 3.3	3980	4510	5190	76.8	87.1	100
400 - 6.3	1405	1790	2130	66.0	84.2	100
550 - 6.0	2090	2700	3320	62.9	81.3	100
700 - 6.3	3020	3620	4280	70.6	84.6	100
400 - 8.9	1110	1450	1670	66.5	86.9	100
550 - 8.2	1930	2320	2550	75.5	90.8	100
700 - 7.9	2550	2950	3300	77.3	89.5	100
400 - 8.7	1070	1450	1640	65.3	88.5	100
550 - 9.0	1760	2110	2360	74.7	89.5	100
700 - 8.8	2870	2880	3110	92.3	92.8	100

TABLE 6.3

RELATIVE COMPRESSIVE STRENGTHS AT VARIOUS AGES,

FOR CONSTANT CEMENT CONTENTS

CEMENT CONTENT OF CONCRETE	AIR CONTENT OF CONCRETE, PER CENT BY VOLUME (ASTM C 231)	RELATIVE COMPRESSIVE STRENGTH AT AGES SHOWN, AS PER CENT OF 28-DAY COMPRESSIVE STRENGTH	
		7 Days	14 Days
400 lb. per cu. yd.	1.6	52.4	77.5
	2.8	57.4	77.4
	4.1	58.3	75.6
	6.3	66.0	84.2
	8.9	66.5	86.9
	8.7	65.3	88.5
550 lb. per cu. yd.	1.4	60.6	79.3
	2.9	72.4	86.5
	3.4	66.8	79.8
	6.0	62.9	81.3
	8.2	75.5	90.8
	9.0	74.7	89.5
700 lb. per cu. yd.	1.3	81.3	89.8
	3.0	81.5	89.8
	3.3	76.8	87.1
	6.3	70.6	84.6
	7.9	77.3	89.5
	8.8	92.3	92.8

TABLE 6.4

EFFECT OF AIR CONTENT ON THE WATER-CEMENT RATIO AND

COMPRESSIVE STRENGTH OF CONCRETE, FOR VARIOUS

CEMENT CONTENTS

CEMENT CONTENT	AIR CONTENT OF CONCRETE, Per Cent by Vol. (ASTM C 231)	NET WATER-CEMENT RATIO BY WEIGHT	AVERAGE 28-DAY COMPRESSIVE STRENGTH p.s.i.
400 lb. per cu. yd.	1.6	0.853	2710
	2.8	0.734	2790
	4.1	0.724	2950
	6.3	0.620	2130
	8.9	0.610	1670
	8.7	0.613	1640
500 lb. per cu. yd.	1.4	0.561	4630
	2.9	0.546	4470
	3.4	0.498	4480
	6.0	0.473	3320
	8.2	0.476	2550
	9.0	0.493	2360
700 lb. per cu. yd.	1.3	0.427	6290
	3.0	0.415	5430
	3.3	0.385	5190
	6.3	0.392	4280
	7.9	0.408	3300
	8.8	0.417	3110

6.2 Weight Loss During Freeze-Thaw Testing

TABLE 6.5

SUMMARY OF WEIGHT LOSS DURING FREEZE-THAW TESTING

MIX	AVERAGE WEIGHT LOSS DURING FREEZE-THAW TESTING, gms.
400 - 1.6	845
550 - 1.4	465
700 - 1.3	246
400 - 2.8	720
550 - 2.9	415
700 - 3.0	222
400 - 4.1	457
550 - 3.4	173
700 - 3.3	73
400 - 6.3	272
550 - 6.0	151
700 - 6.3	71
400 - 8.9	241
550 - 8.2	129
700 - 7.9	67
400 - 8.7	227
550 - 9.0	114
700 - 8.8	65

6.3 Freeze-Thaw Durability Test Results

TABLE 6.6

CONCRETE DURABILITY FACTORS FOR VARIOUS CEMENT CONTENTS

CEMENT CONTENT	AIR CONTENT OF CONCRETE, Per Cent by Volume (ASTM C 231)	DURABILITY FACTOR, Per Cent
400 lb. per cu. yd.	1.6	4.2
	2.8	31.4
	4.1	48.1
	6.3	74.9
	8.9	85.2
	8.7	84.7
550 lb. per cu. yd.	1.4	6.8
	2.9	35.9
	3.4	52.2
	6.0	76.2
	8.2	84.0
	9.0	86.0
700 lb. per cu. yd.	1.3	18.6
	3.0	38.2
	3.3	54.6
	6.3	77.7
	7.9	83.8
	8.8	86.2

6.3 Freeze-Thaw Durability Test Results

6.4 Microscopic Analysis Test Results

TABLE 6.7

SUMMARY OF MICROSCOPIC ANALYSIS DATA

MIX	SPECIFIC SURFACE OF VOIDS, sq. in. per cu. in.	VOID SPACING FACTOR, in.	DURABILITY FACTOR, Per Cent	AVERAGE CHORD INTERCEPT, in.
400 - 1.6	246	0.0382	4.2	0.01625
550 - 1.4	341	0.0358	6.8	0.01170
700 - 1.3	427	0.0340	18.6	0.00938
400 - 2.8	476	0.0291	31.4	0.00840
550 - 2.9	498	0.0249	35.9	0.00805
700 - 3.0	542	0.0194	38.2	0.00738
400 - 4.1	595	0.0112	48.1	0.00672
550 - 3.4	632	0.0094	52.2	0.00633
700 - 3.3	678	0.0088	54.6	0.00590
400 - 6.3	789	0.00592	74.9	0.00507
550 - 6.0	954	0.00564	76.2	0.00419
700 - 6.3	1040	0.00530	77.7	0.00382
400 - 8.9	980	0.00538	85.2	0.00408
550 - 8.2	1010	0.00493	84.0	0.00396
700 - 7.9	1095	0.00482	83.8	0.00365
400 - 8.7	1025	0.00461	84.7	0.00391
550 - 9.0	1060	0.00479	86.0	0.00377
700 - 8.8	1130	0.00458	86.2	0.00355

TABLE 6.8

COMPARISON OF AIR CONTENT DATA FOR FRESH CONCRETE

(BY PRESSURE METER) AND HARDENED CONCRETE (BY A.S.T.M. OPTICAL METHOD)

MIX	AIR CONTENT OF FRESH CONCRETE BY PRESSURE METER, Per Cent by Volume (ASTM C 231)	AIR CONTENT OF HARDENED CONCRETE BY MICROSCOPIC EXAMINATION, Per Cent by Volume (ASTM C 457)
400 - 1.6	1.6	1.09
550 - 1.4	1.4	0.617
700 - 1.3	1.3	0.439
400 - 2.8	2.8	0.400
550 - 2.9	2.9	0.592
700 - 3.0	3.0	0.965
400 - 4.1	4.1	2.24
550 - 3.4	3.4	3.15
700 - 3.3	3.3	3.43
400 - 6.3	6.3	4.44
550 - 6.0	6.0	3.80
700 - 6.3	6.3	4.12
400 - 8.9	8.9	3.33
550 - 8.2	8.2	4.46
700 - 7.9	7.9	4.45
400 - 8.7	8.7	4.30
550 - 9.0	9.0	4.30
700 - 8.8	8.8	4.75
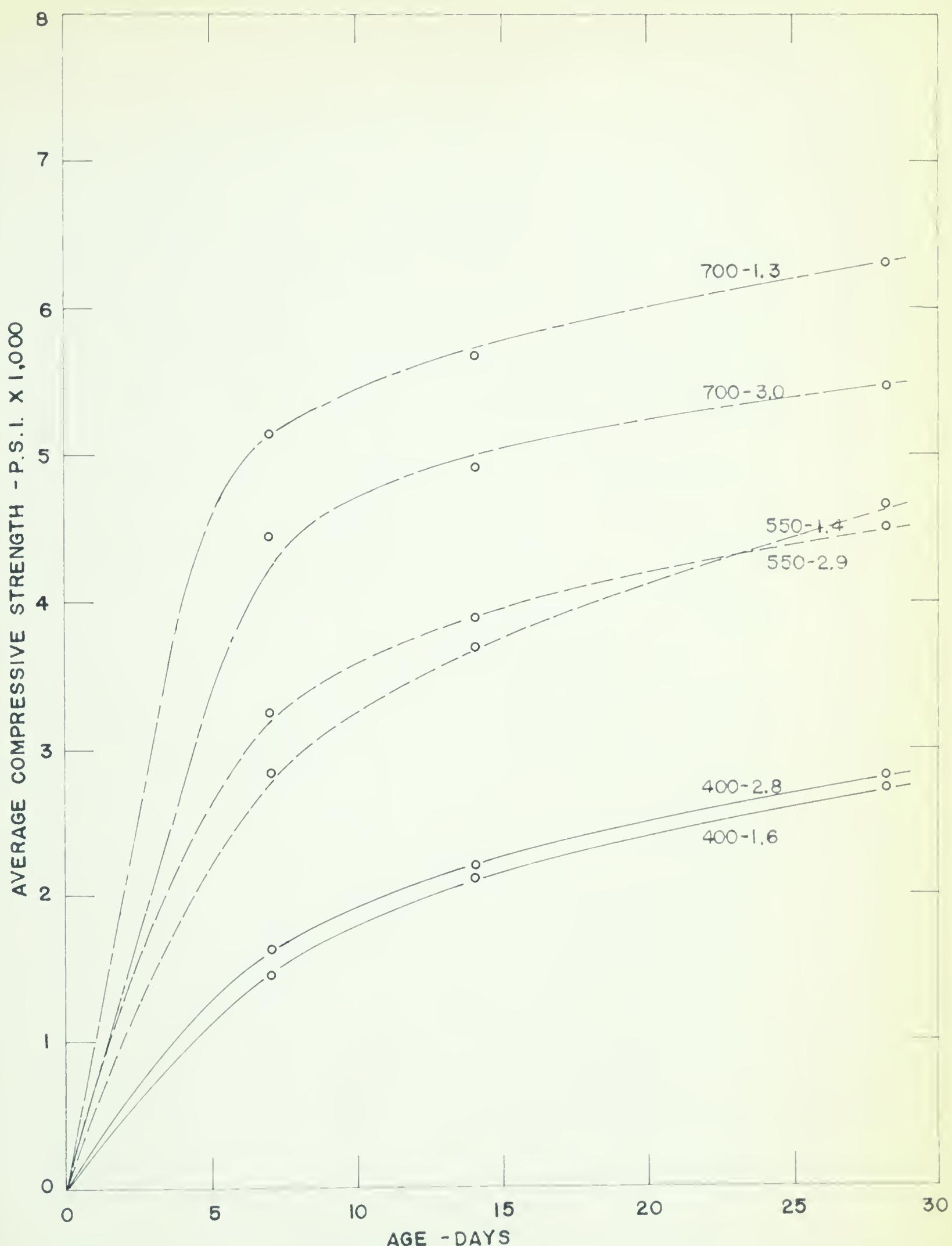
FIGURE 6.1 –Relationship Between Average Compressive
Strength and Age, for Average Air Contents
of 1.4% and 2.9%
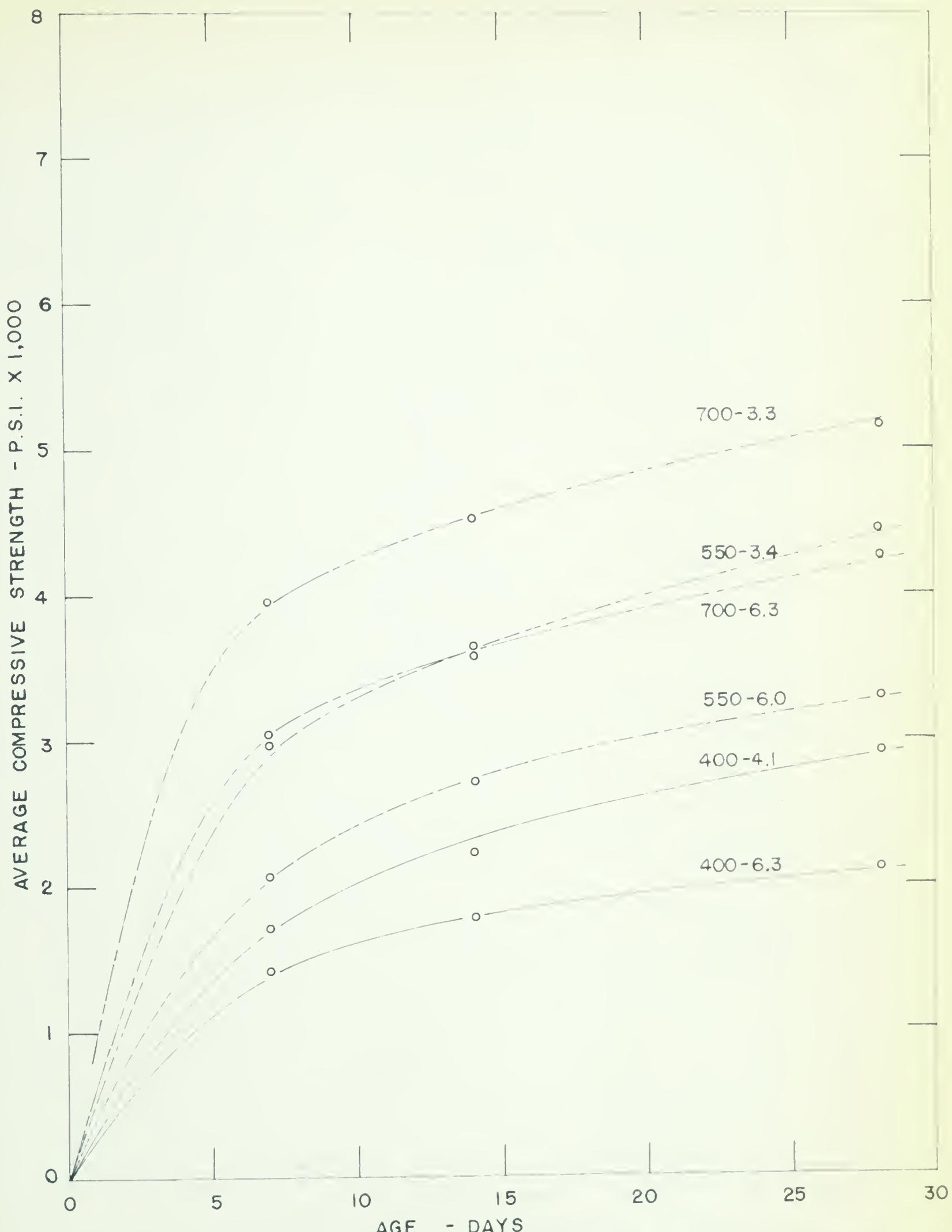
FIGURE 6.2 - Relationship Between Average Compressive Strength and Age, for Average Air Contents of 3.6% and 6.2%
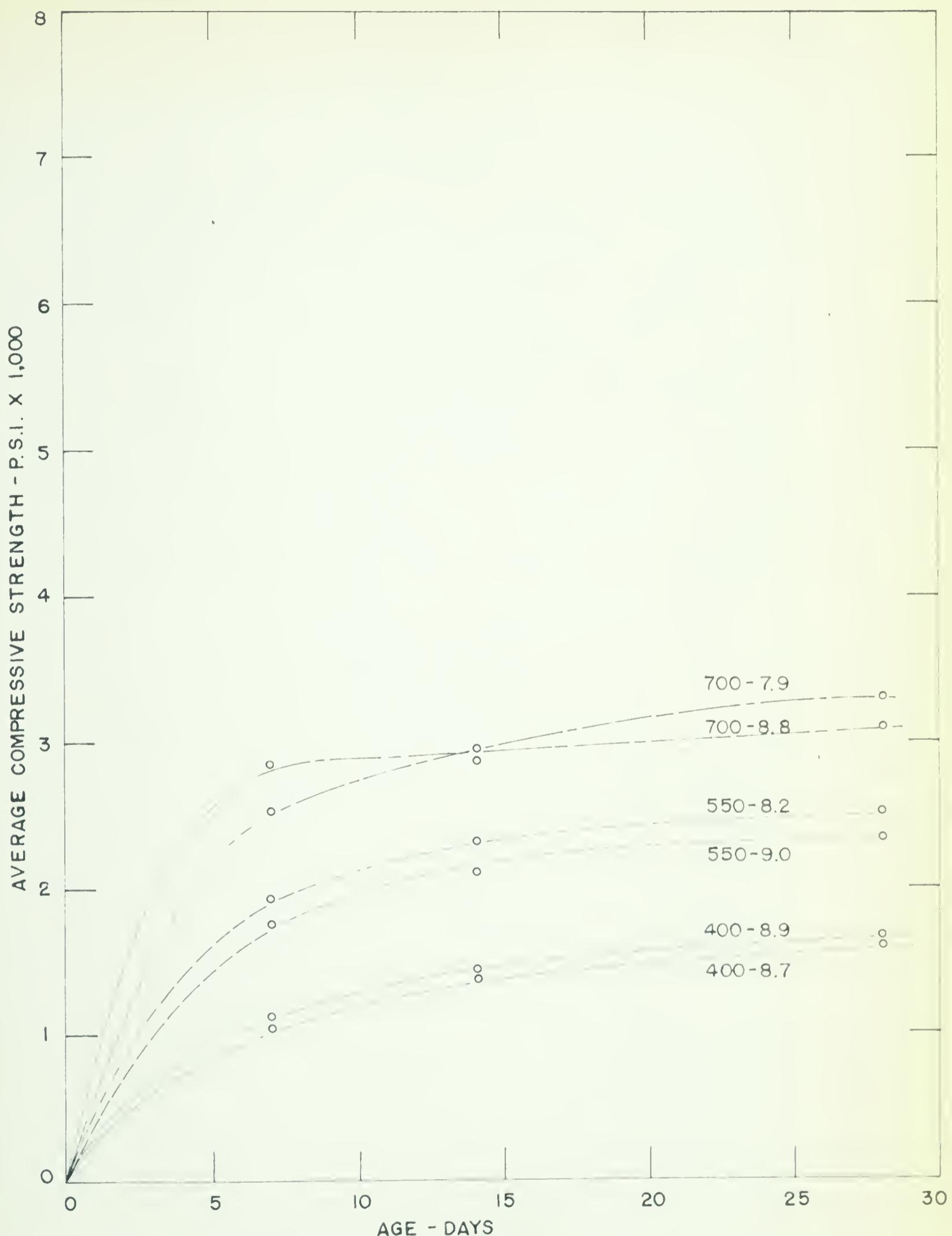
FIGURE 6.3 - Relationship Between Average Compressive
Strength and Age, for Average Air Contents
of 8.3% and 8.8%
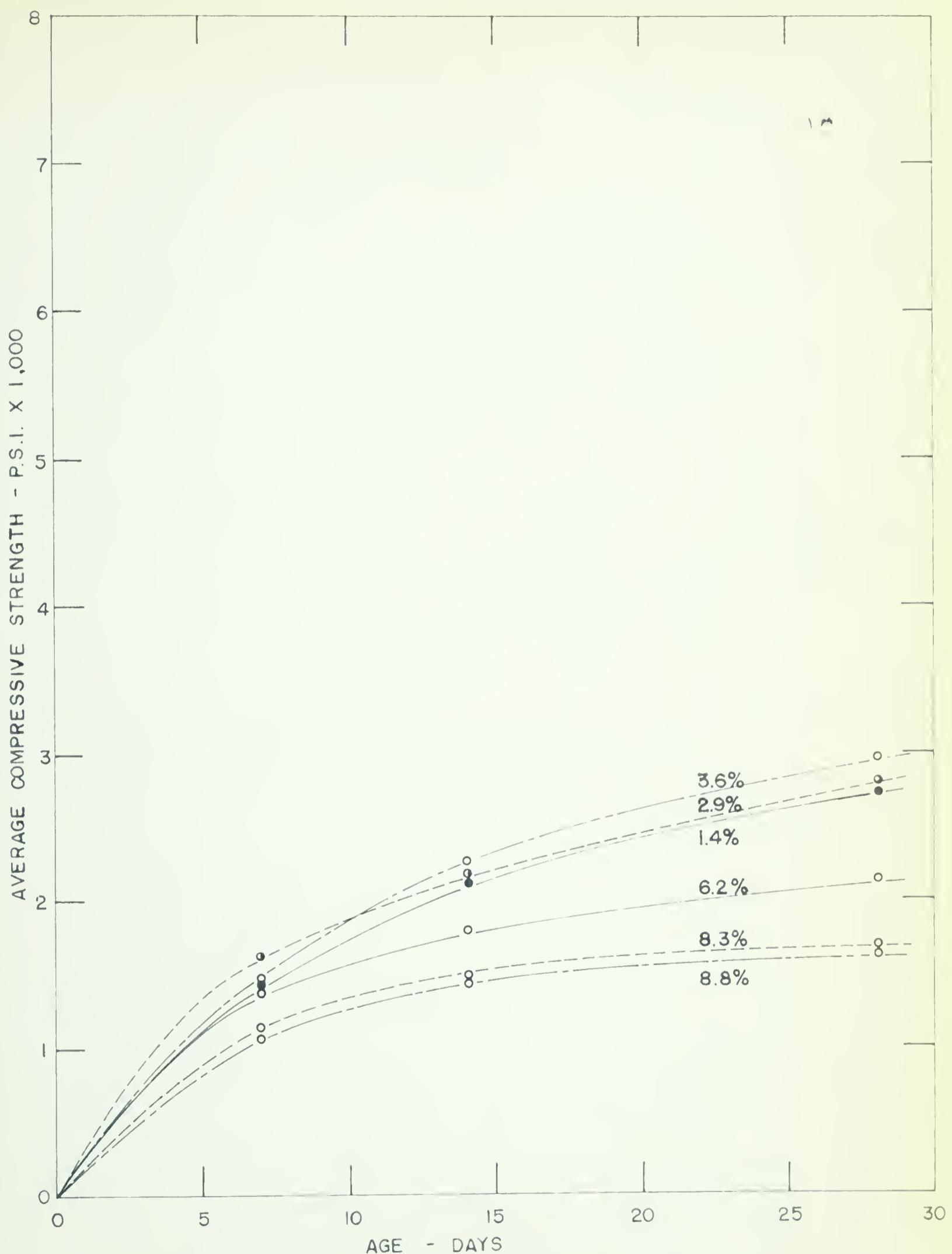
FIGURE 6.4 - Relationship Between Average Compressive
Strength and Age of Concrete, for Various Average
Air Contents, and Cement Content of 400 lb./cu.yd.
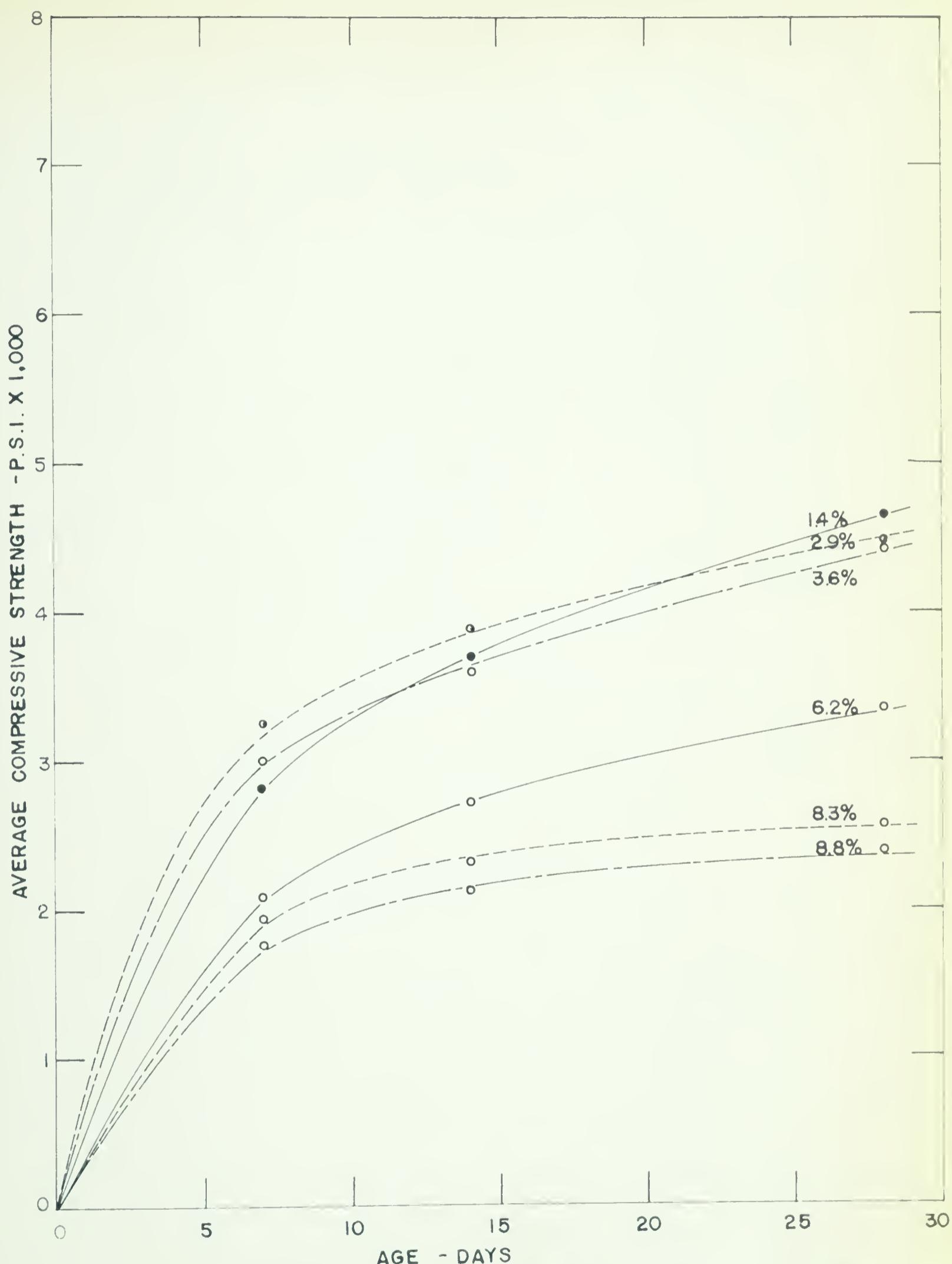
FIGURE 6.5 - Relationship Between Average Compressive
Strength and Age of Concrete , for Various Average
Air Contents, and Cement Content of 550 lb./cu.yd.
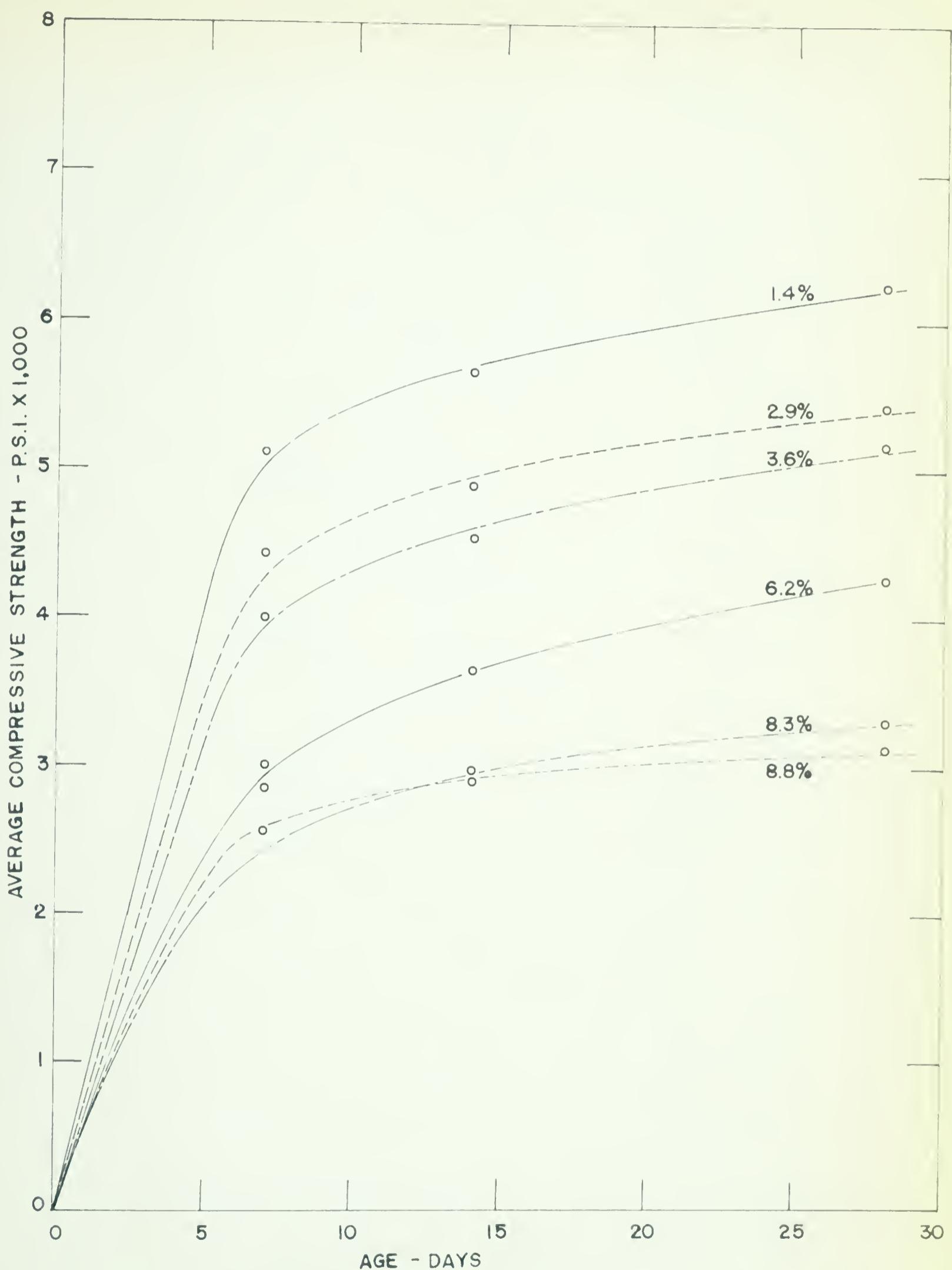
FIGURE 6.6 – Relationship Between Average Compressive Strength and Age of Concrete, for Various Average Air Contents, and Cement Content of 700 lb./cu. yd.
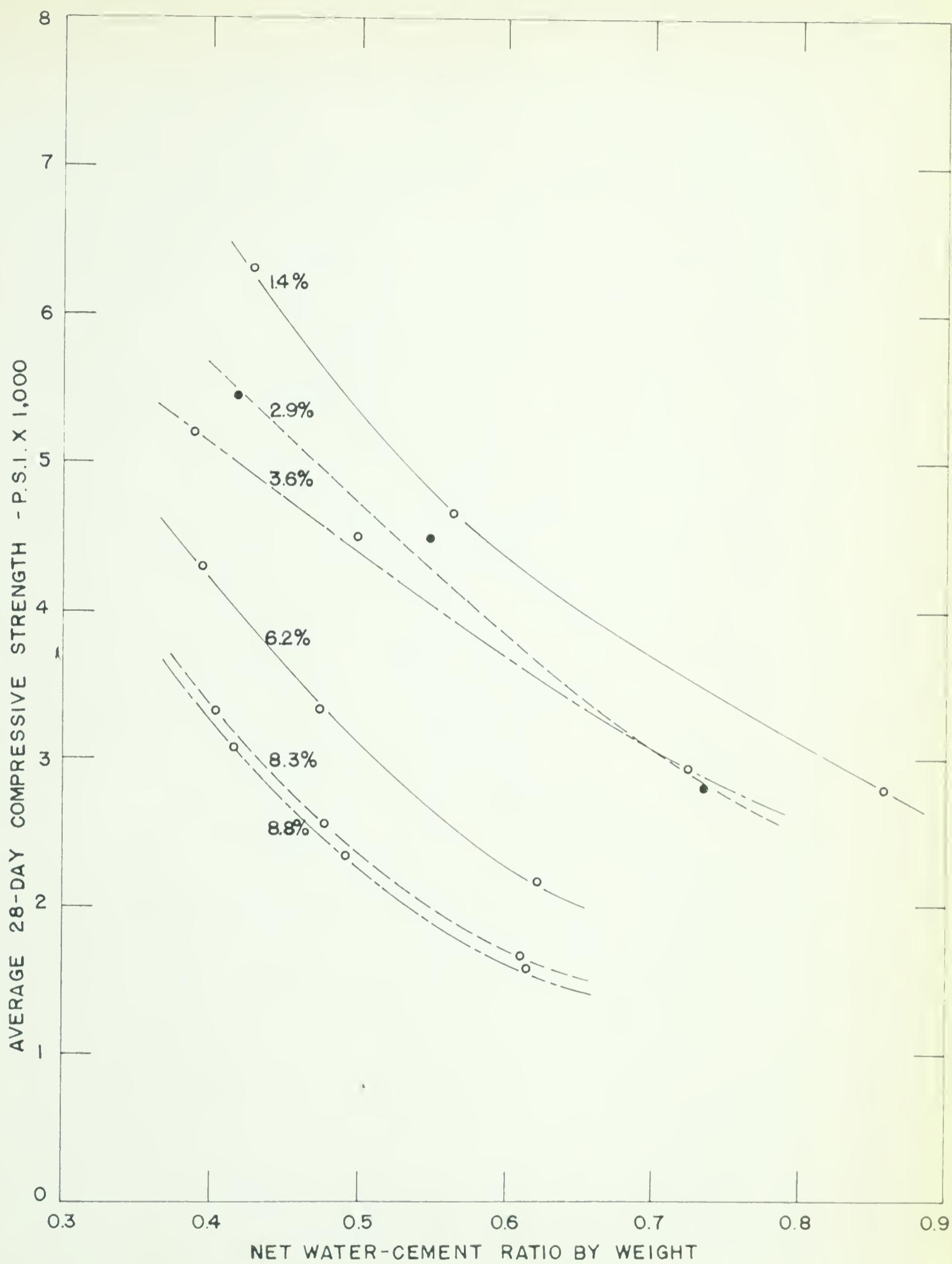
FIGURE 6.7 – Relationship Between 28-Day Compressive
Strength and Water-Cement Ratio, for Various
Average Air Contents
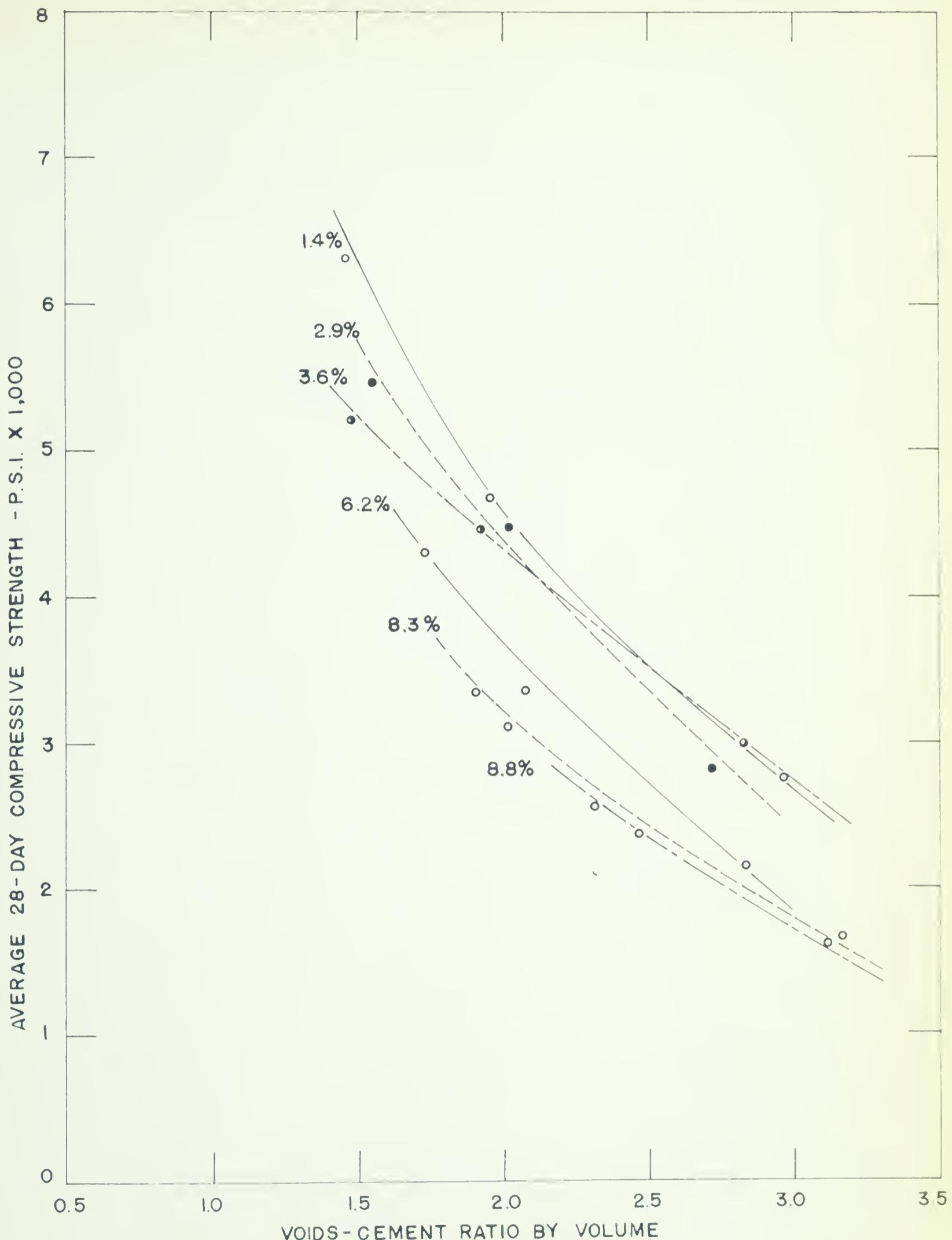
FIGURE 6.8 – Relationship Between 28-Day Compressive Strength and Voids-Cement Ratio, for Various Average Air Contents
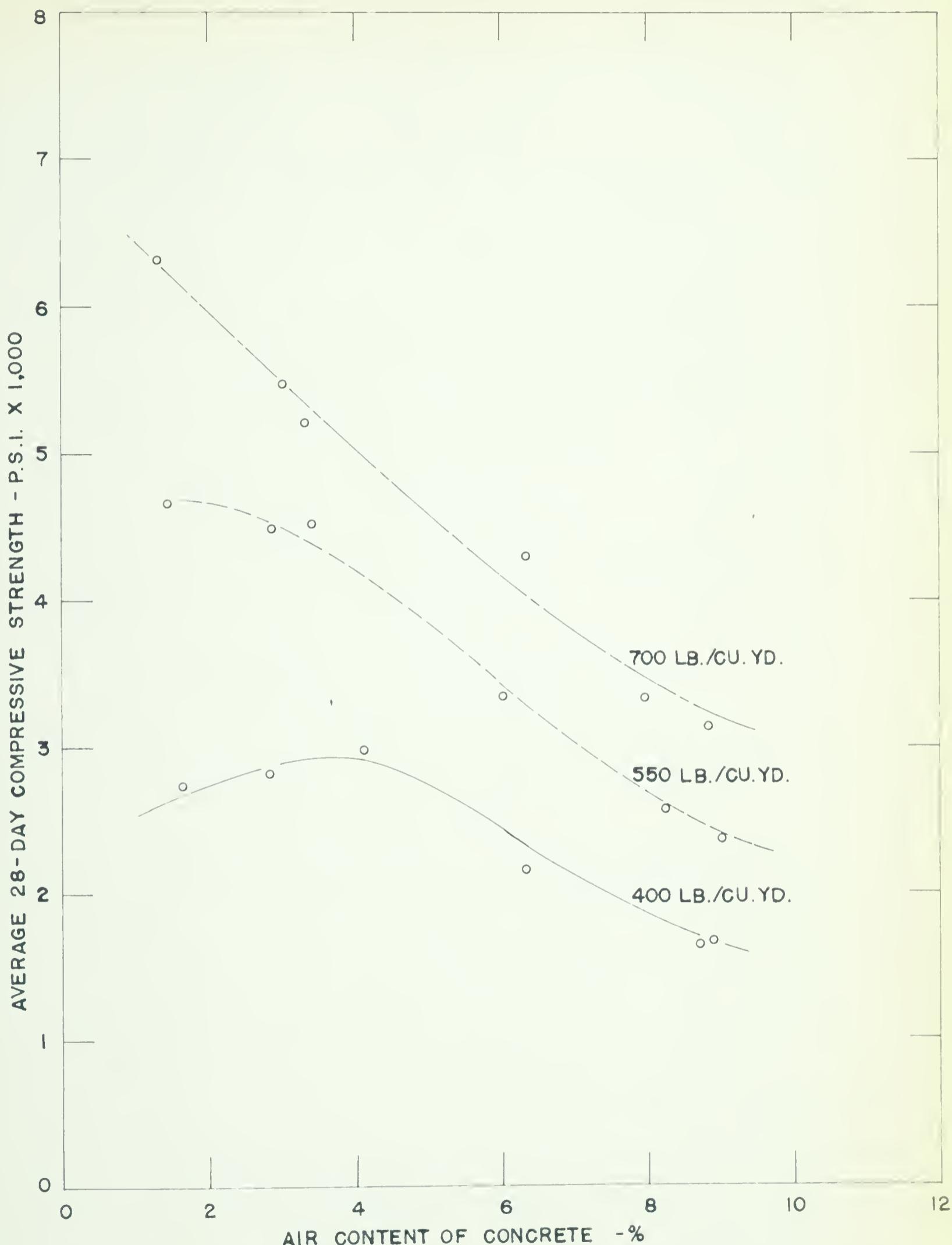
FIGURE 6.9 – Effect of Air Content on The Average Compressive Strength of Concrete, For Various Cement Contents
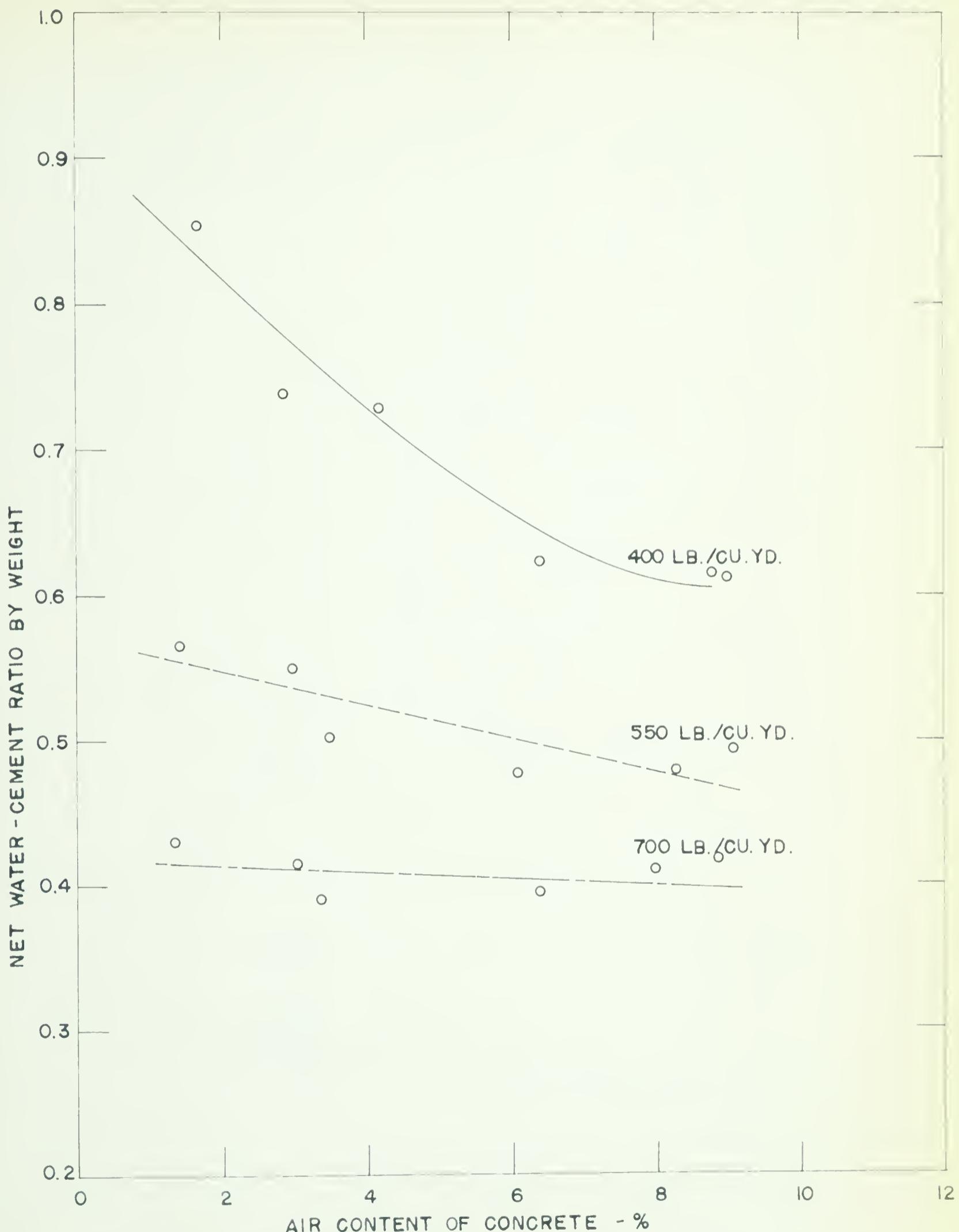
FIGURE 6.10 - Effect of Air Content on The Water - Cement Ratio of Concrete, for Various Cement Contents
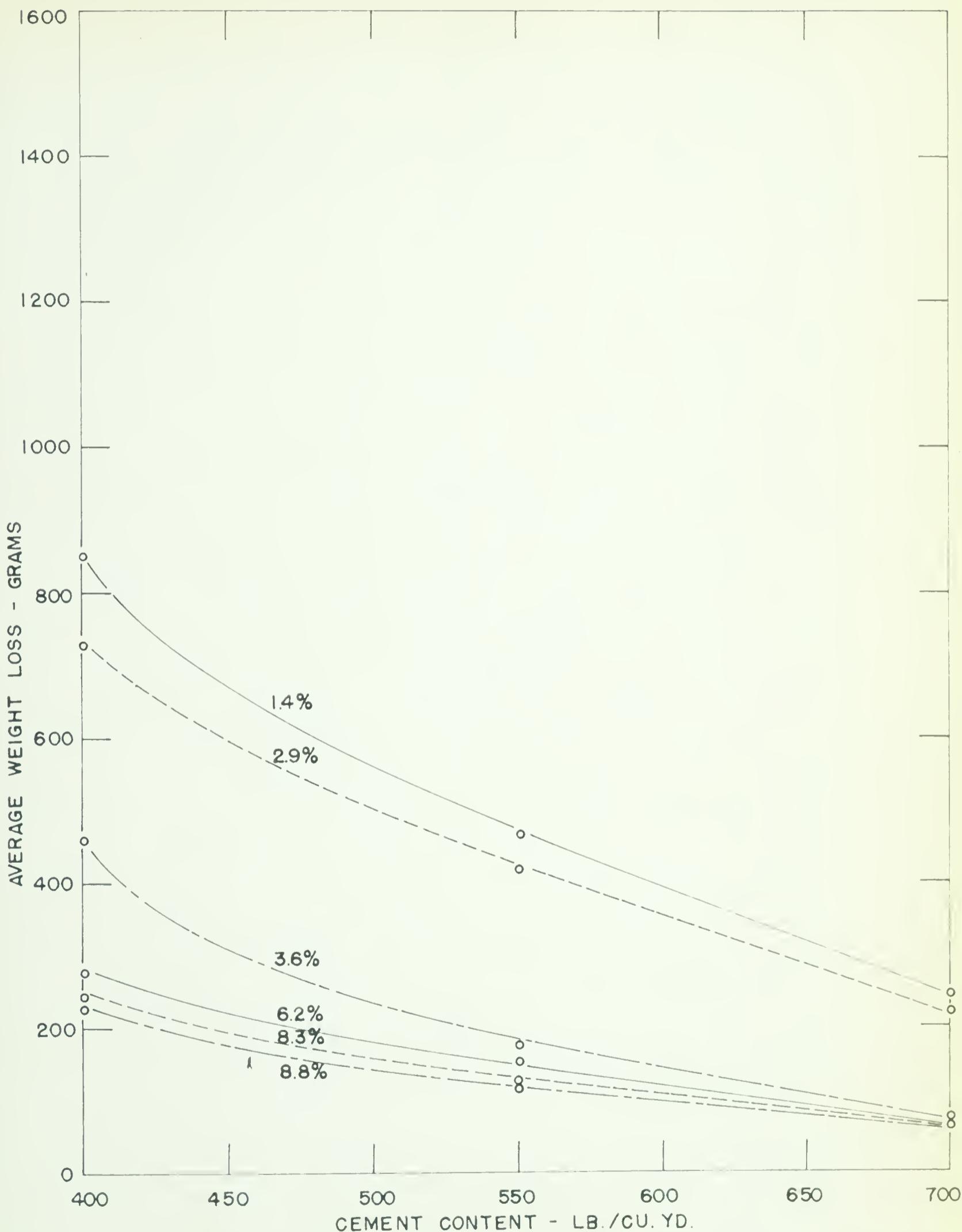
FIGURE 6.11 - Relationship Between Weight Loss During
Freeze - Thaw Testing and Cement Content, for
Various Average Air Contents
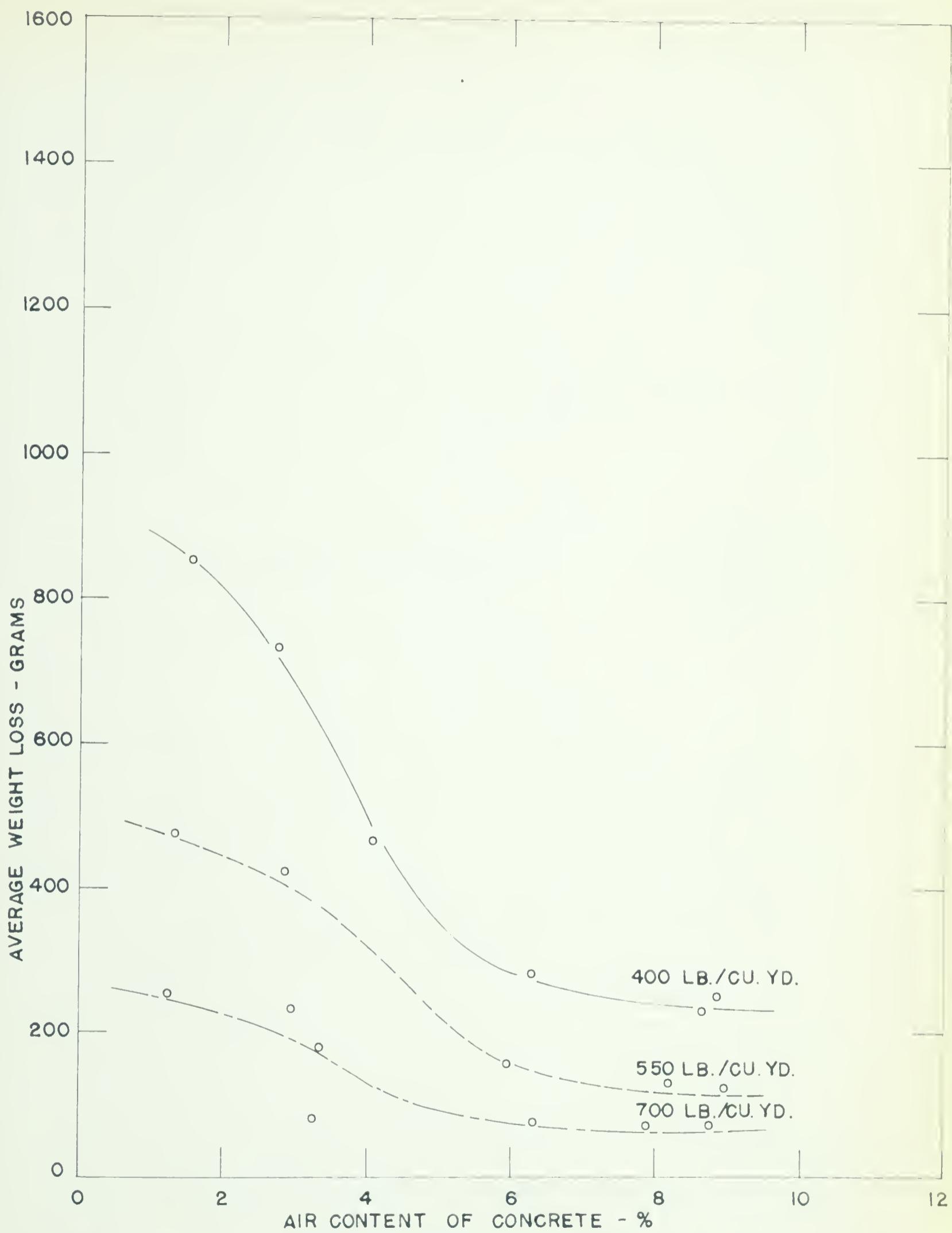
FIGURE 6.12 - Relationship Between Weight Loss During
Freeze -Thaw Testing and Air Content of Concrete,
for Various Cement Contents
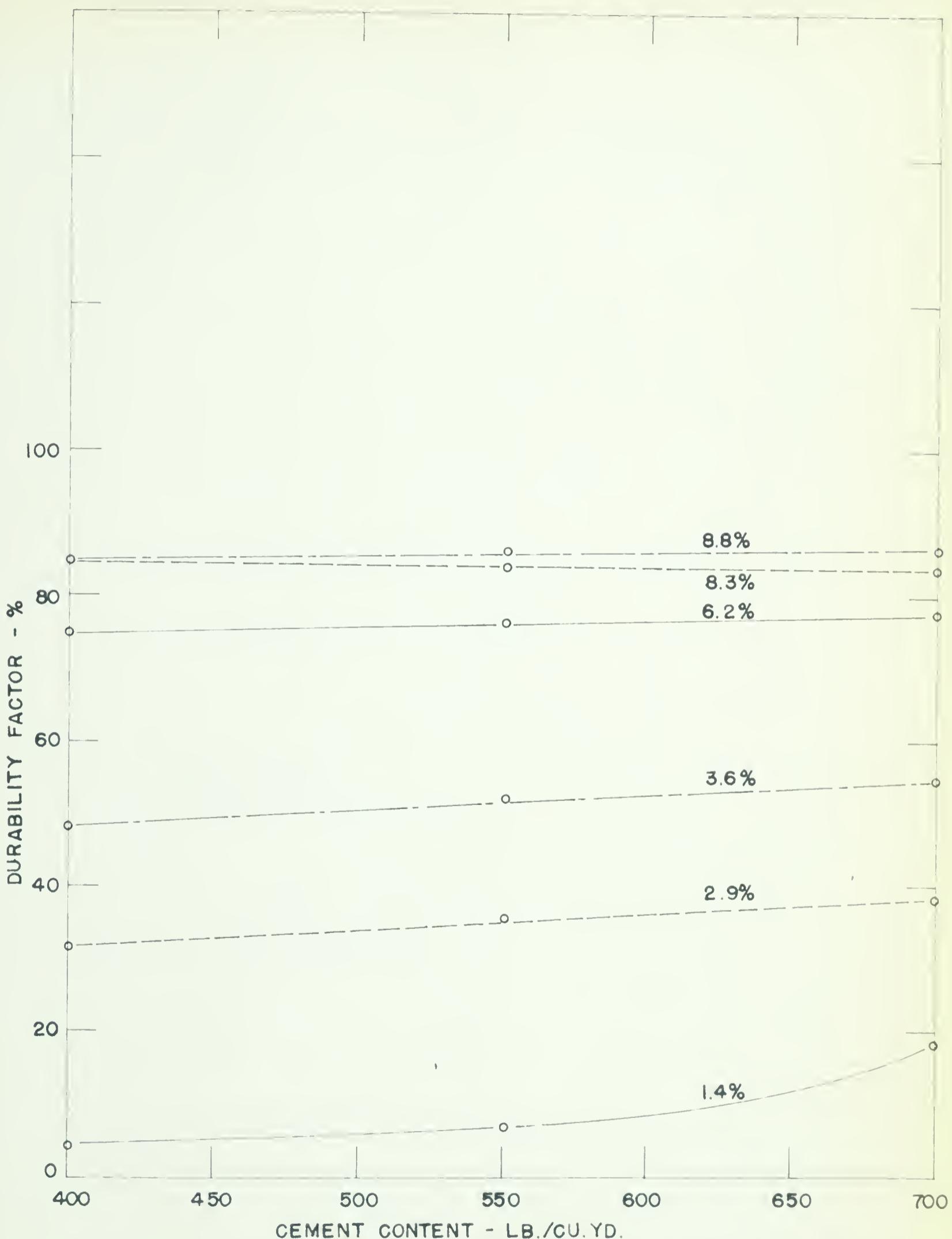
FIGURE 6.13- Relationship Between Durability Factor
and Cement Content, for Various Average Air Contents
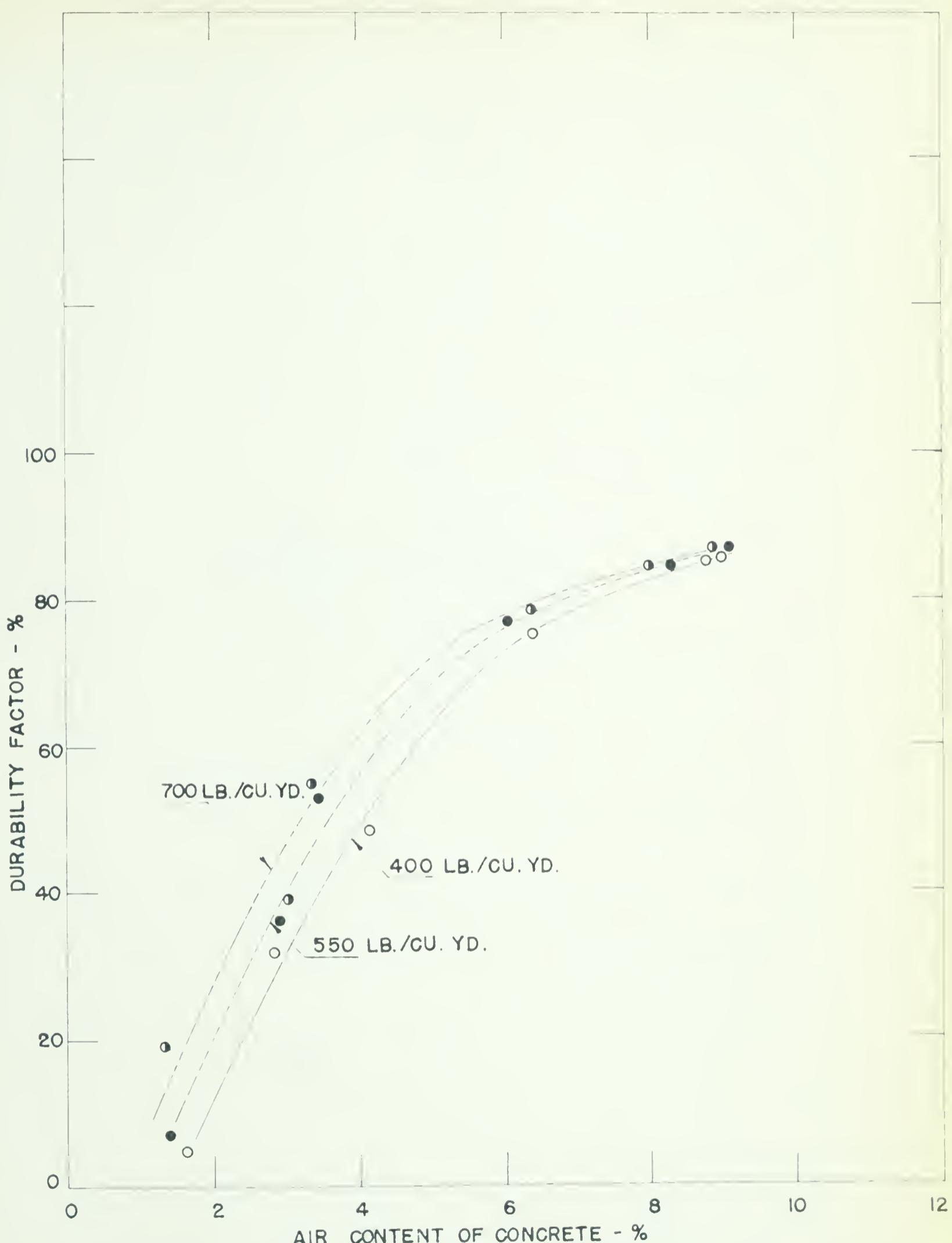
FIGURE 6.14 - Relationship Between Durability Factor and Air Content of Concrete, for Various Cement Contents
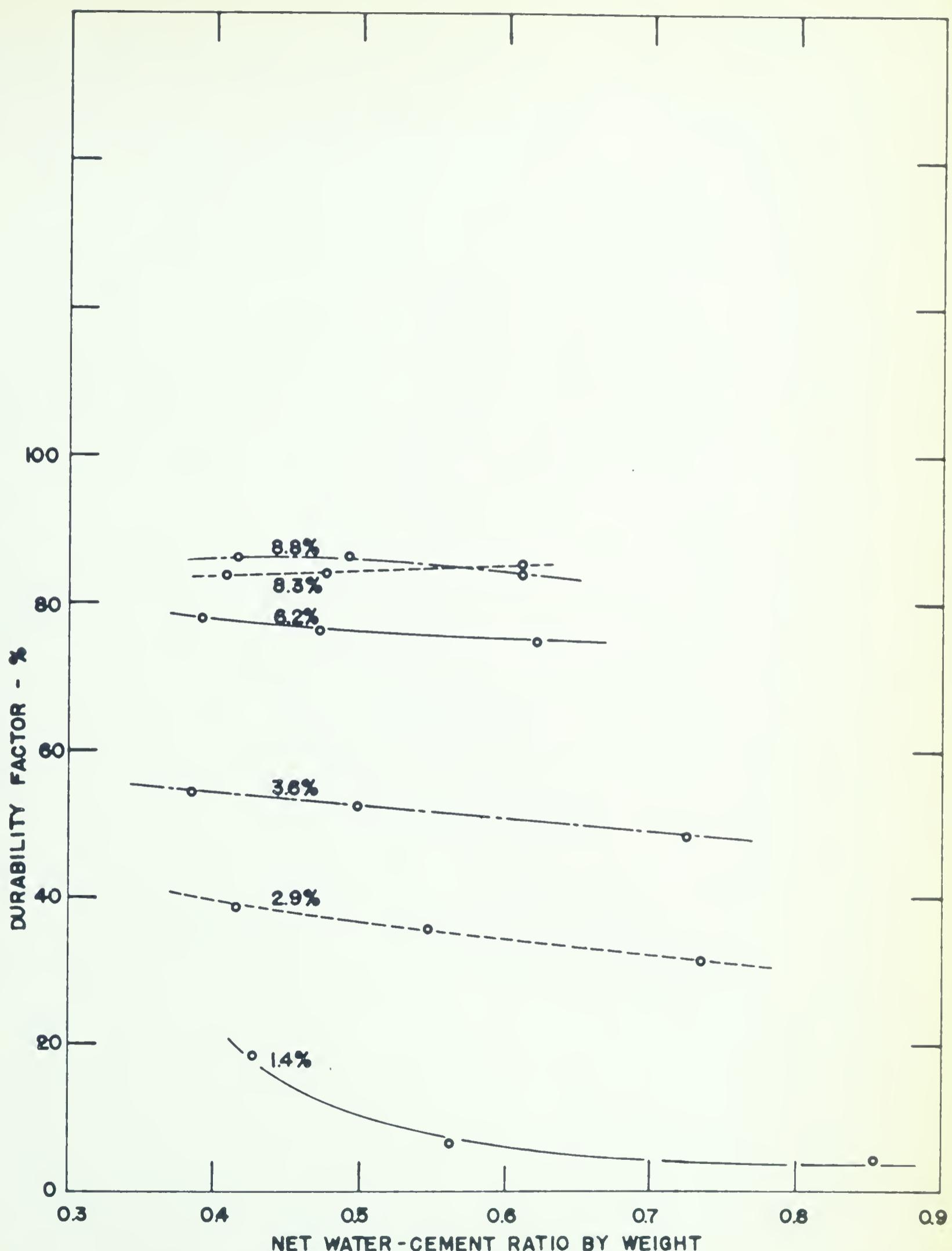
FIGURE 6.15- Relationship Between Durability Factor
and Water-Cement Ratio, for Various Average
Air Contents
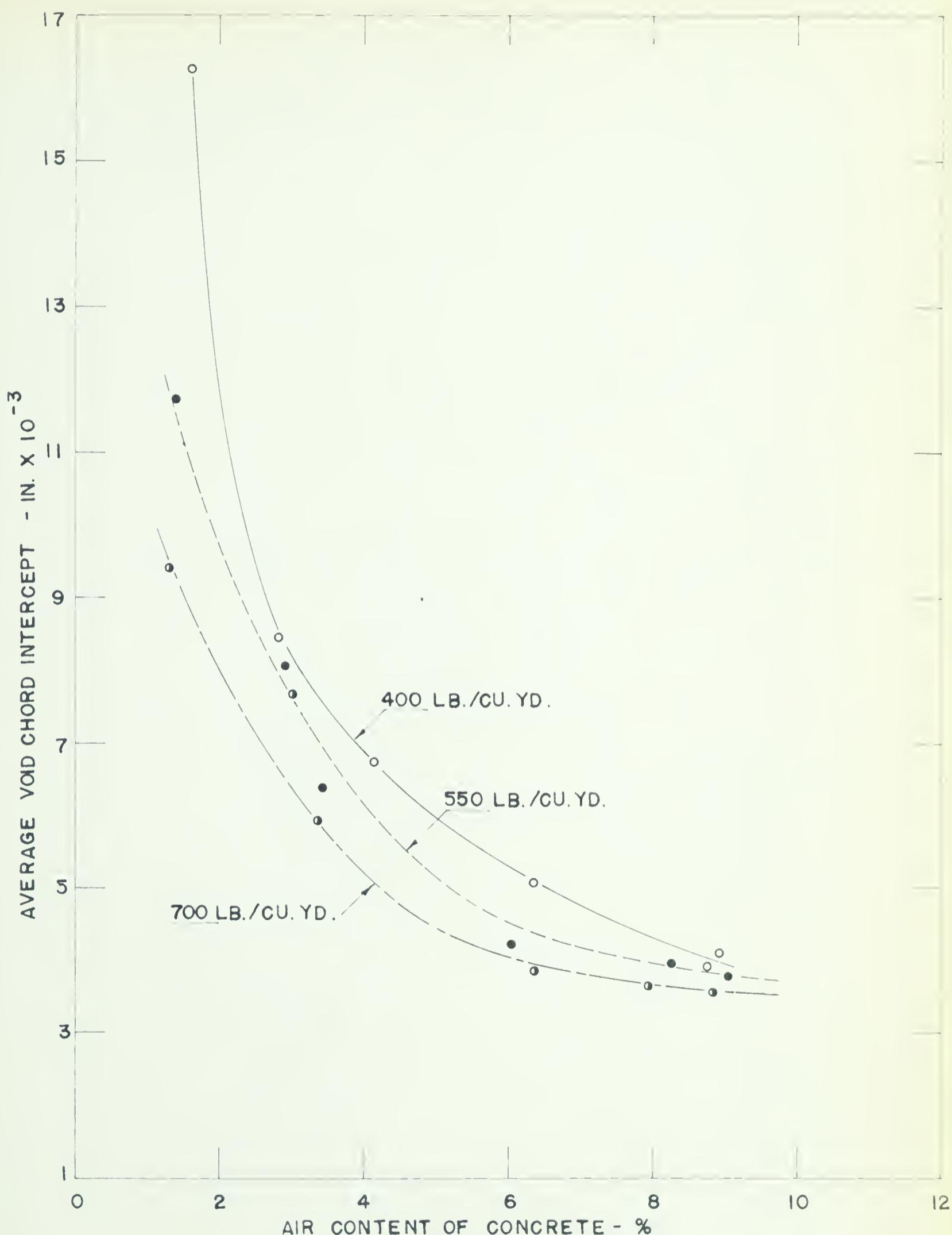
FIGURE 6.16- Relationship Between Chord Intercept of
Voids and Average Air Content of Concrete,
for Various Cement Contents
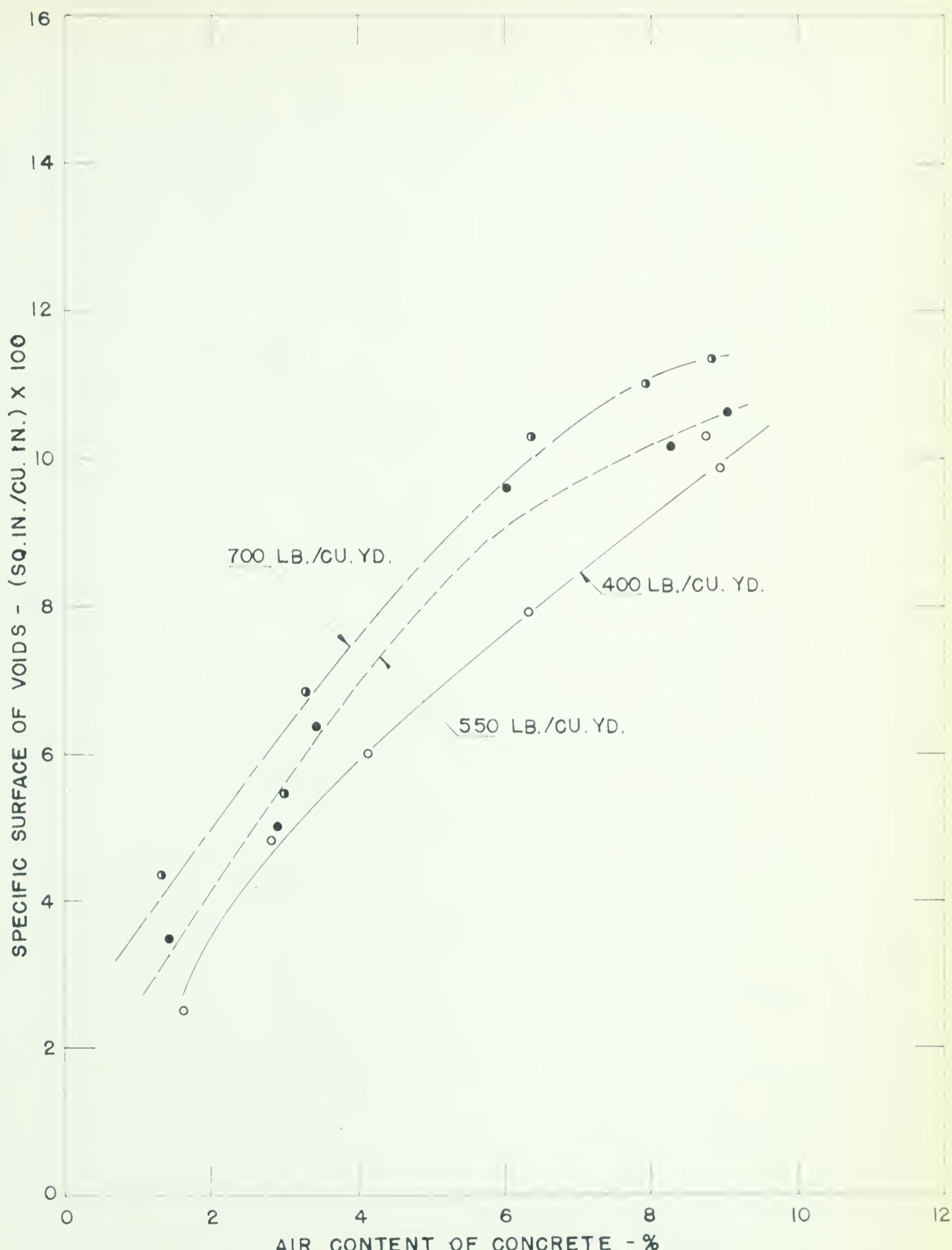
FIGURE 6.17 - Relationship Between Specific Surface of Voids and Average Air Content of Concrete, for Various Cement Contents
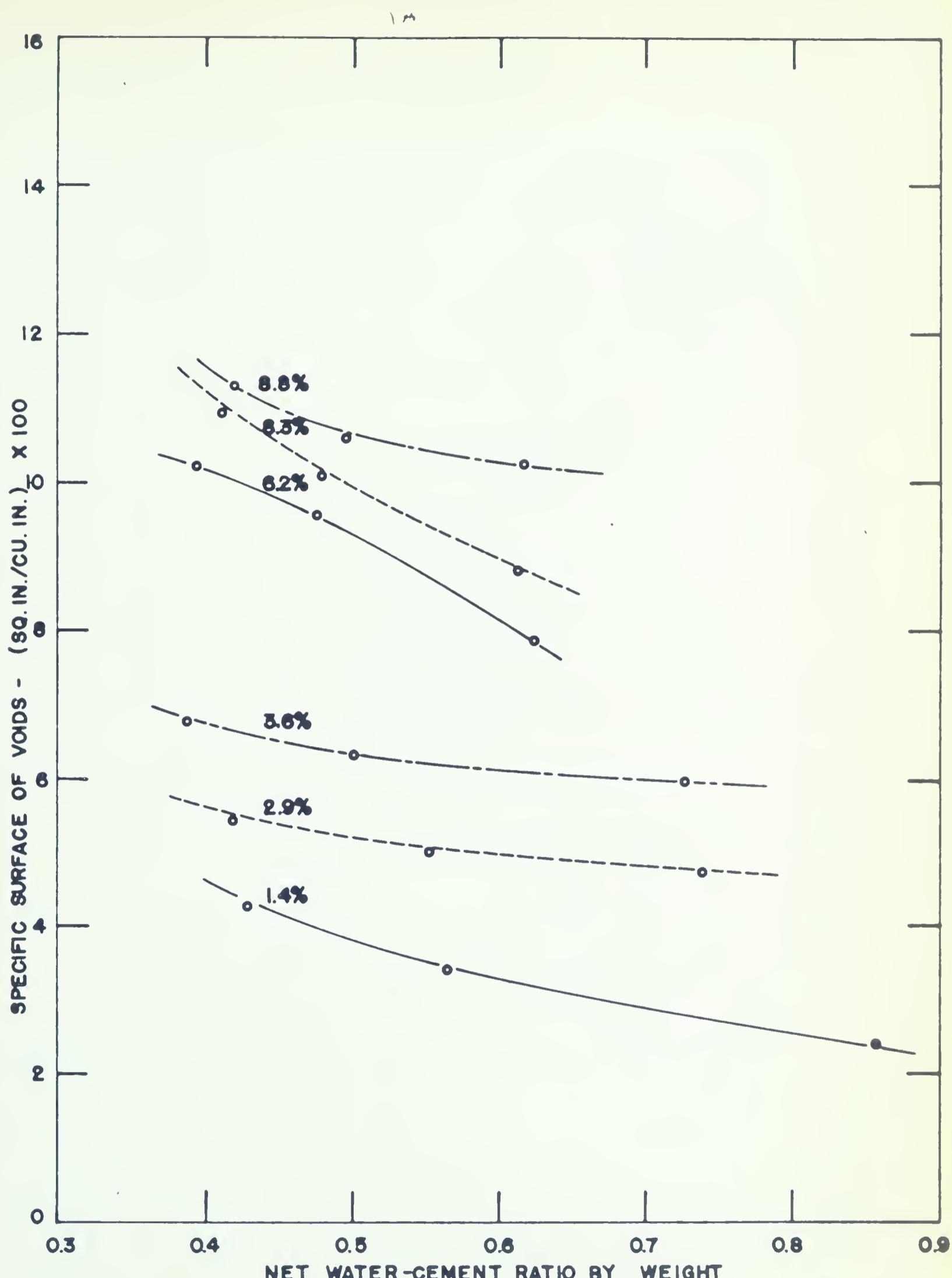
FIGURE 6.18 - Relationship Between Specific Surface of Voids and Water-Cement Ratio, for Various Average Air Contents
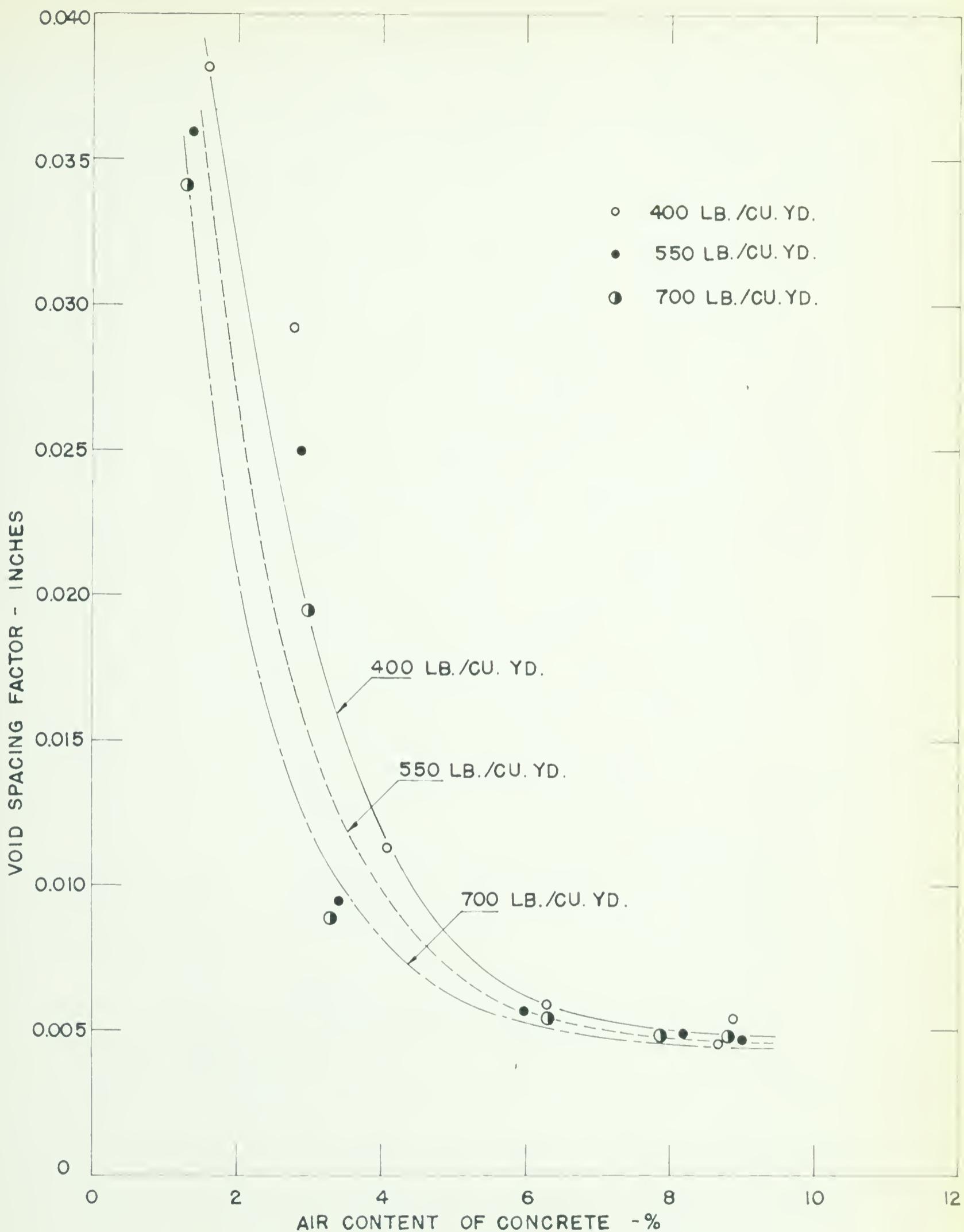
FIGURE 6.19 - Relationship Between Void Spacing Factor
and Air Content of Concrete, for Various
Cement Contents
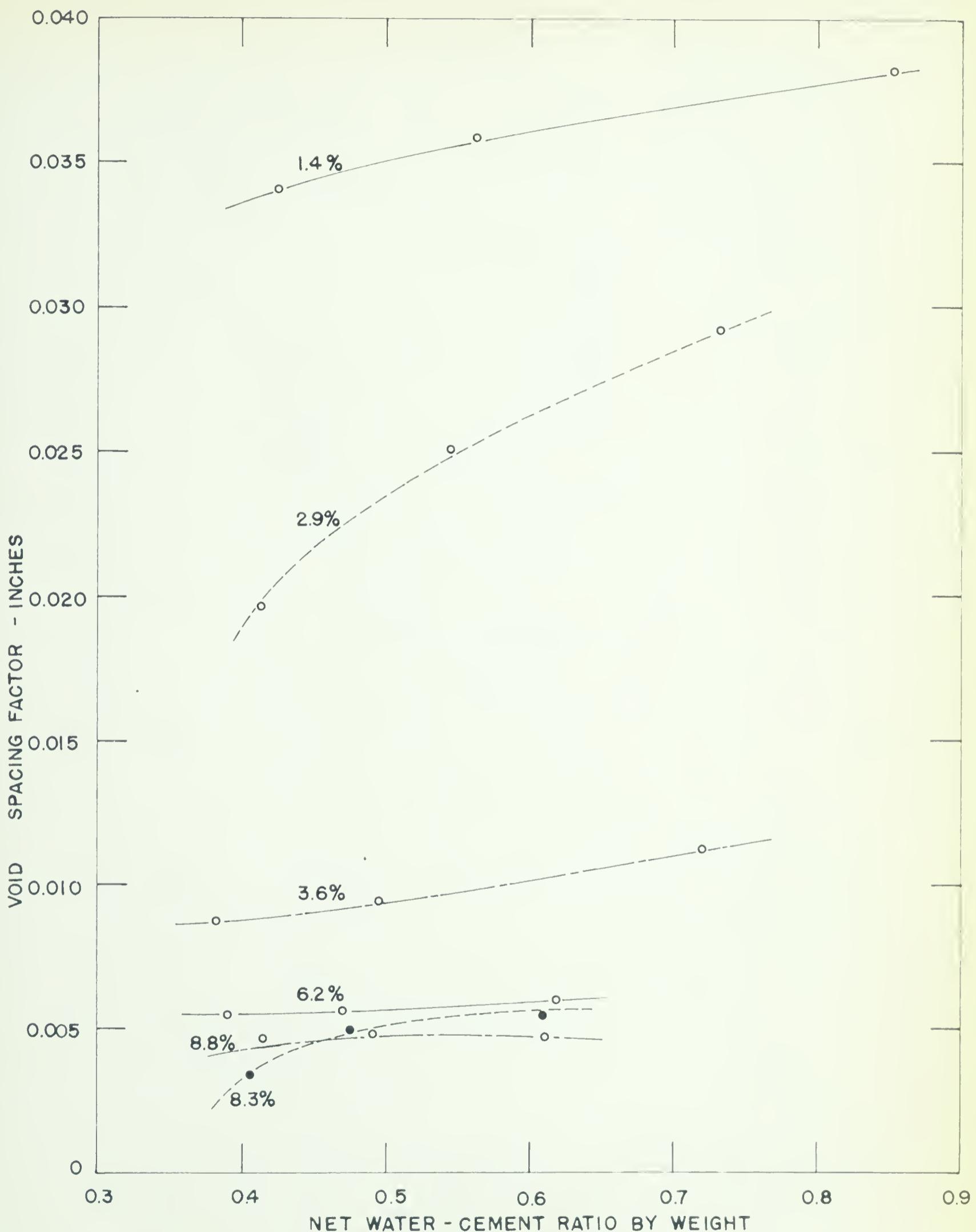
FIGURE 6.20-Relationship Between Void Spacing Factor
and Water-Cement Ratio, for Various Average
Air Contents
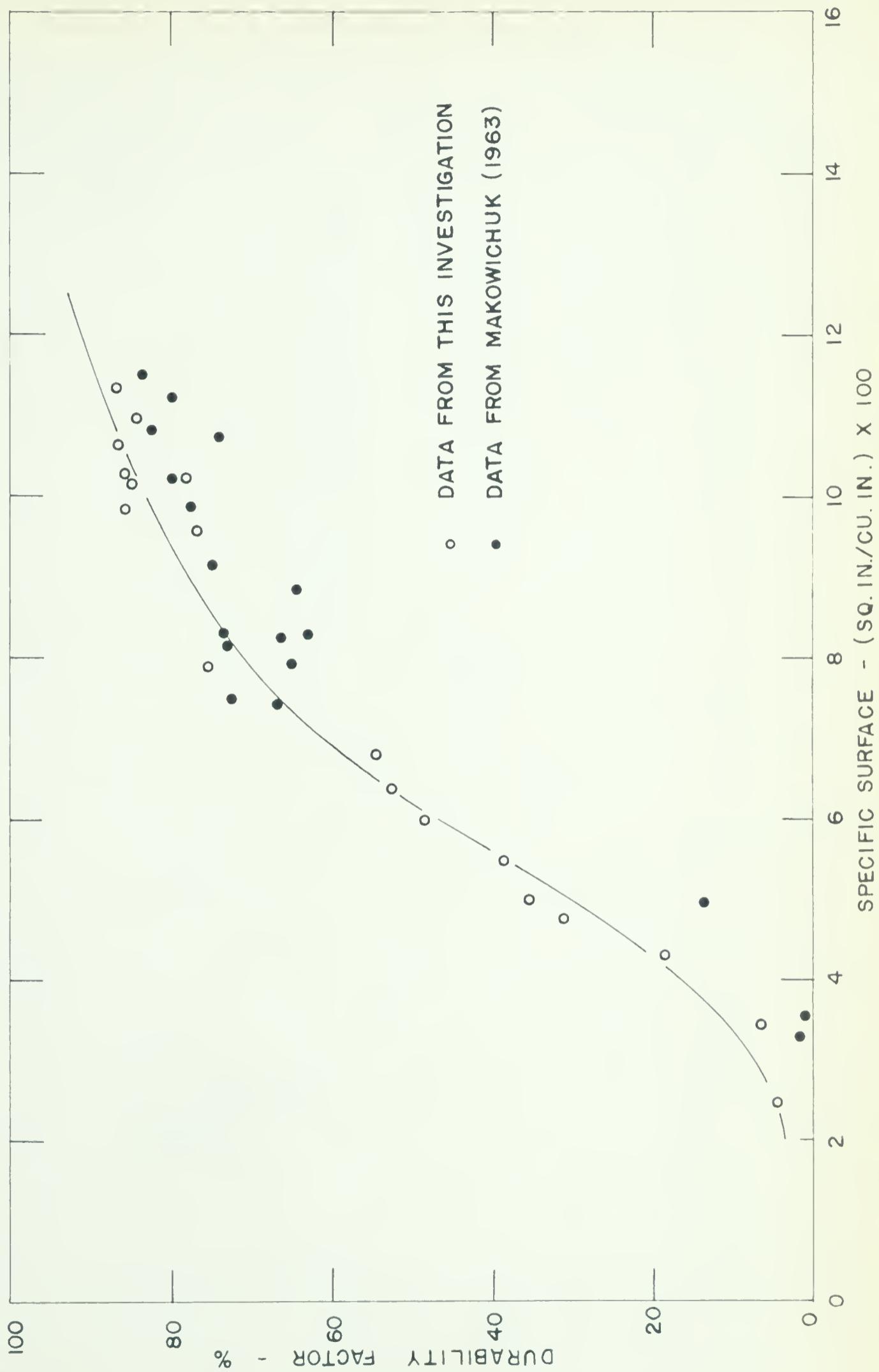
FIGURE 6.21-Relationship Between Durability Factor and Specific Surface of Voids
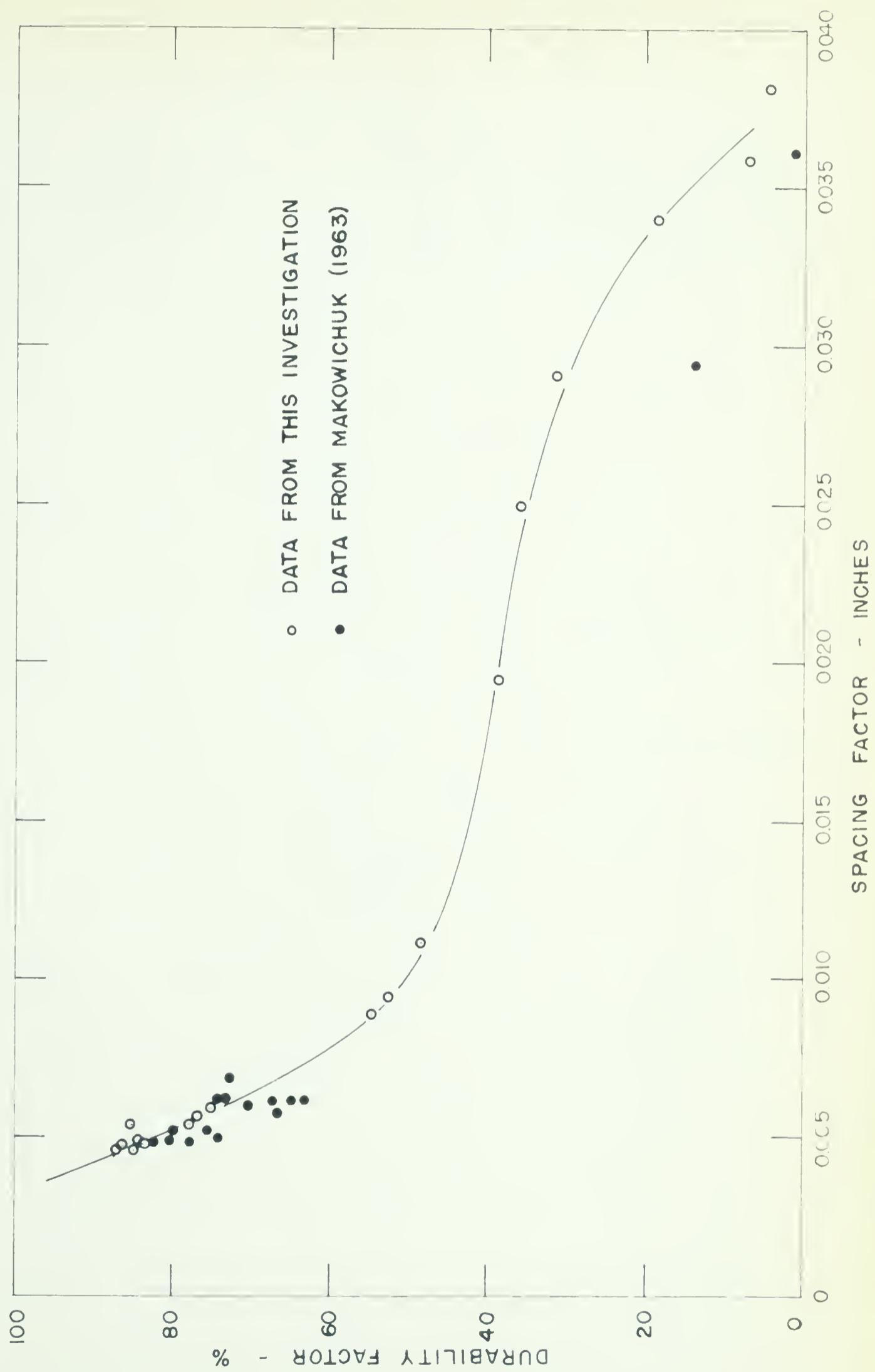
FIGURE 6.22 - Relationship Between Durability Factor and Void Spacing Factor
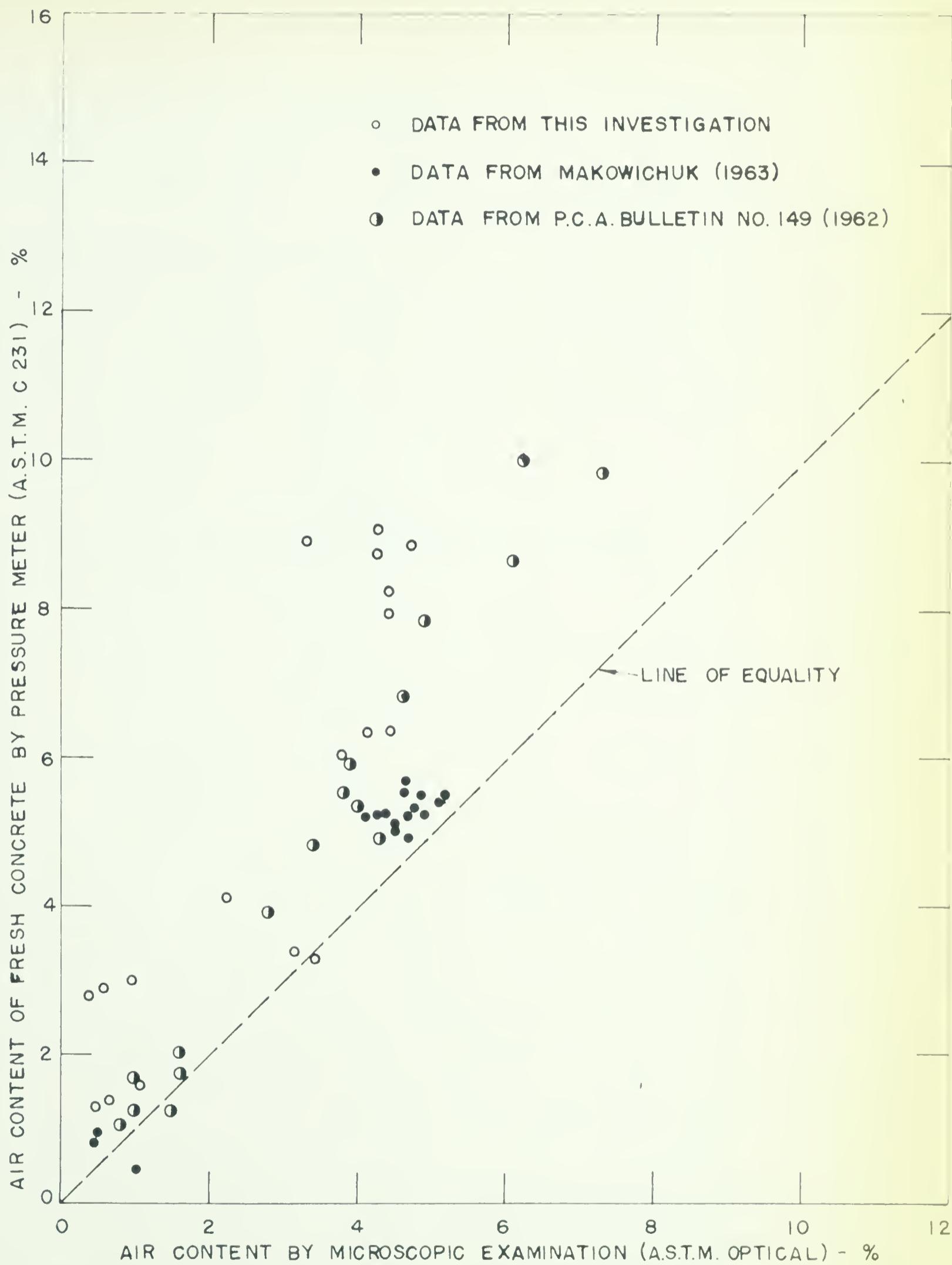
FIGURE 6.23 -Comparison of Air Content Data
for Fresh Concrete (by pressure meter) and
Hardened Concrete (by A.S.T.M. optical method)

CHAPTER 7

DISCUSSION AND INTERPRETATION OF TEST RESULTS

CHAPTER 7

DISCUSSION AND INTERPRETATION OF TEST RESULTS

7.1 Compressive Strength Results

TABLES 6.1 to 6.4 inclusive, and FIGURES 6.1 to 6.6 inclusive, relate the concrete compressive strengths to their ages. FIGURES 6.1, 6.2, and 6.3 show relationships for various air contents, while FIGURES 6.4, 6.5, and 6.6 are for various cement contents.

A study of these compressive strength data shows that:

(a) for a constant air content, compressive strength increases as cement content increases, and

(b) in the richer mixes, compressive strength generally decreases as air content increases. As the mixes become leaner, the strength reductions accompanying increased air content are decreased.

FIGURE 6.7 verifies the well-known inverse relationships between average compressive strength and water-cement ratio. From FIGURE 6.7, it is seen that:

(a) compressive strength does, in fact, decrease as the water-cement ratio increases, for any air content, and

(b) for any water-cement ratio, compressive strength decreases as air content increases.

FIGURE 6.8 relates average compressive strength to voids-cement ratio by volume. The curves in this figure have essentially the same form as those in FIGURE 6.7, and show that:

(a) compressive strength decreases, as voids-cement ratio increases, and

(b) compressive strength generally decreases as air content increases, for any voids-cement ratio.

If the theory is accepted that concrete strength is dependent only upon the density of the cement paste in the hardened mass (Powers and Brownyard, 1948), a plot of strength versus voids-cement ratio would result in a unique curve.

Although the data presented in FIGURE 6.8 do not form a single curve, they do define a narrower band than do the relationships between concrete strength and water-cement ratio (FIGURE 6.7).

The significance of the band of values in FIGURE 6.8 is to show that, at any voids-cement ratio (i.e. paste density) there is a range of compressive strengths exhibited, with varying air content. It is thus concluded that the compressive strength of concrete is dependent on factors in addition to the cement paste density.

7.2 Effect of Air Content on Compressive Strength and Water-Cement
Ratio of Concrete

FIGURE 6.9 shows the effect of air content on the average compressive strength of concrete, for various cement contents. A study of this figure shows that:

(a) for any air content, compressive strength increases as cement content increases,

(b) for any cement content, compressive strength generally decreases as air content increases, and

(c) the strength reduction accompanying air entrainment decreases

as concrete becomes leaner. There appears to be an "optimum air content" at which the lean and medium mixes (i.e those with cement content 400 and 550 lb. per cu. yd.) exhibit a peak strength. This maximum strength reflects the large reduction in water requirements for such mixes, with increasing air content.

FIGURE 6.10 relates the water-cement ratio and air content of concrete, for various cement contents, and shows in another form the data presented in FIGURE 6.9. Lean mixes show relatively great reductions in required water, with increasing air content.

7.3 Relative Compressive Strength at Various Ages

TABLES 6.2 and 6.3 summarize data concerning the relative compressive strength development at various ages, for the concretes tested. Available data show that:

(a) for any air content, the rate of compressive strength development increases as cement content increases, and

(b) the rate of compressive strength development increases as air content increases, for the lean mixes; in the richer mixes, however, the rate of strength gain is almost independent of air content.

7.4 Weight Loss During Freeze-Thaw Testing

TABLE 6.5, and FIGURES 6.11 and 6.12 summarize data concerning weight loss of concrete specimens during freeze-thaw testing. The data show that:

(a) weight loss during freeze-thaw testing decreases as cement content increases, for any air content,

(b) weight loss decreases as air content increases, for any cement content,

(c) the reduction in weight loss resulting from air entrainment is more pronounced in lean mixes than in rich mixes, and

(d) the reduction in weight loss resulting from increased cement content is most pronounced at low (i.e. less than 4%) air contents; above approximately 4% air, cement content has relatively little effect on weight loss of concrete during freezing and thawing.

7.5 Freeze-Thaw Durability Test Results

FIGURES 6.13, 6.14, and 6.15 relate durability to cement content, air content, and water-cement ratio, respectively. These data are also summarized in TABLE 6.6.

Analysis of freeze-thaw data shows that:

(a) for constant air content, durability increases slightly as cement content increases; the durability increase is so little that it is concluded that durability is practically independent of cement content, for a given air content,

(b) for constant air content, durability decreases slightly as water-cement ratio increases; the decrease in durability is so little, however, that durability may be considered independent of water-cement ratio, particularly for air contents in excess of approximately 2%,

(c) for any cement content, durability increases as air content increases. FIGURE 6.14 shows that the effect of cement content on durability, although minor, is most pronounced

at air contents below approximately 6%; all mixes behave
essentially alike with respect to durability, at air
contents above approximately 6%, and

(d) greater improvement of durability can be realized by air
entrainment than by increasing the cement content of
concrete.

7.6 Microscopic Analysis Data

TABLE 6.7, FIGURES 6.16, 6.17, 6.18, 6.19, and 6.20 summarize
data for microscopic analyses performed in this investigation. A study
of these data reveals that:

(a) for a constant cement content, increased air content
results in;

   (i) decreased length of void chord intercept,

   (ii) increased specific surface of voids, and

   (iii) decreased void spacing factor,

(b) for a constant water-cement ratio, increased air content
results in;

   (i) increased specific surface of voids, and

   (ii) decreased void spacing factor,

(c) for a constant air content, increased cement content
results in;

   (i) decreased void chord intercept,

   (ii) decreased void spacing factor, and

   (iii) increased specific surface of voids,

(d) the void spacing factor decreases rapidly as the air content
of concrete is increased to approximately 6%; at air con-
tents greater than approximately 6%, spacing factor is

practically independent of both cement content and air
content,

(e) the void chord intercept decreases rapidly as the air
content of concrete is increased to approximately 6%;
at air contents greater than approximately 6%, the void
chord intercept is practically independent of both
cement content and air content,

(f) the water-cement ratio has practically no effect on the
specific surface of voids, for air contents up to approxi-
mately 6%, and

(g) the water-cement ratio has practically no effect on the
void spacing factor in concrete.

7.7 Correlation of Freeze-Thaw Durability Data and Microscopic Analysis
Data

FIGURES 6.21 and 6.22 summarize the most significant results
of this investigation, since they relate data from freeze-thaw testing
and microscopic analysis.

FIGURE 6.21 shows the relationship between durability and the
specific surface of voids. The shape of the curve indicates that there
is a range of specific surface (from approximately 300 to 800 sq. in. per
cu. in.), over which increases in specific surface cause large improvement
in durability. At low (less than approximately 300 sq. in. per cu. in.),
and high (more than 800 sq. in. per cu. in.), values of specific surface,
changes in specific surface cause little change in durability.

FIGURE 6.22 relates durability to void spacing factor. The
data show that durability increases rapidly as the void spacing factor
decreases from about 0.01 inch to about 0.005 inch. As the spacing factor

increases beyond approximately 0.01 inch, the rate of loss of durability is at a reduced rate.

The value of critical spacing factor obtained in this investigation (approximately 0.005 inch), is seen to be of the same order of magnitude as that suggested by Powers (1955), for rapid freezing, as discussed in CHAPTER 2.

FIGURES 6.21 and 6.22 include data both from this investigation, and those obtained by Makowichuk (1963). The agreement between the two sets of data is generally good, although the relationships between durability and both specific surface and spacing factor are not linear.

7.8 Comparison of Air Content Data For Fresh and Hardened Concrete

FIGURE 6.23 compares air content data for fresh concrete (obtained by the air pressure meter), and hardened concrete (obtained by the A.S.T.M. optical method). Three sets of data are plotted in FIGURE 6.23, viz

(i) data from this investigation,

(ii) data from Makowichuk (1963), and

(iii) data from P.C.A. Bulletin No. 149 (1962).

Although there is considerable "spread" of the plotted data, the following conclusions are drawn:

(a) Microscopic examination of hardened concrete yields air content values which are almost always lower than those obtained for the fresh concrete, using the air pressure meter.

This discrepancy may be partially explained by the fact that microscopic examination excludes entrapped air and water voids, whereas the pressure meter data include these volumes of air. Supplemental microscopic analysis

of several specimens, with air measurements including
entrapped air and water voids, failed to significantly
change the air content as obtained when these quantities
were neglected.

(b) There appears to be an upper limit of air content (approxi-
mately six per cent) above which the method of microscopic
examination is unable to accurately determine the air content
of hardened concrete. Possible explanations of this
apparent upper limit may include one or more of the following:

(i) the inability of the investigator to prepare a good
polished surface of concrete for microscopic examination,
at high (i.e. above six per cent) air contents,

(ii) the presence of a constant error in the pressure meter
used for air content determinations of the fresh concrete,
and

(iii) the possibility that air is lost from the concrete during
vibration of the specimens.

The compressive strength cylinders and beam specimens
were cast in two layers, and externally vibrated for
approximately 20 seconds. The fresh concrete specimens
whose air contents were measured by the air pressure
meter were, however, not vibrated.

Lerch (1960) reported the loss of approximately two
to three per cent air (by volume) as a result of vibration,
in concretes of air content four to six per cent (measured
in fresh concrete). In concretes of higher air content,
the reduction in air content accompanying concrete

vibration could be expected to be greater than the two to three per cent quoted by Lerch.

If a significant quantity of entrained air was, in fact, vibrated out of the cast specimens, the upper limit of air contents in the hardened concrete in this study might well have been five to six per cent by volume, rather than the nine per cent indicated by air pressure meter measurements of fresh concrete.

The relatively constant value of air void parameters at air contents nominally greater than six per cent might therefore be partially due to the fact that the air content in the hardened concrete never attained the value measured in the fresh concrete (and used in all figures where "Air Content" was plotted).

CHAPTER 8

MAJOR CONCLUSIONS FROM THIS INVESTIGATION, AND

RECOMMENDATIONS FOR FUTURE RESEARCH

CHAPTER 8

MAJOR CONCLUSIONS FROM THIS INVESTIGATION, AND

RECOMMENDATION FOR FUTURE RESEARCH

8.1 Major Conclusions From This Investigation

With respect to relationships between concrete freeze-thaw
durability and air void parameters, major conclusions from this investigation
are:

(1) Increasing the entrained air content of concrete up to
approximately 6% has the effects of:

(a) decreasing the average air void size,

(b) decreasing the air void spacing,

(c) increasing the specific surface of the voids,
and

(d) increasing the freeze-thaw durability, as a result
of the effects (a), (b), and (c).

(2) There is little practical advantage in air entrainment beyond
approximately 6%, since the air void parameters of size,
spacing, and surface area are relatively constant above this
air content.

(3) Relationships between concrete durability and both specific
surface and spacing factor are non-linear.

(4) The sharp transition from relatively "good" to "bad" freeze-
thaw durability with increasing void spacing indicates that
the critical spacing factor of voids is approximately 0.005

inch, for test conditions of this study.

(5) Freeze-thaw durability of concrete is practically independent of cement content and water-cement ratio, for air contents above approximately 2% and the range of water-cement ratios investigated.

(6) Protection of concrete from freeze-thaw deterioration is more effectively realized by air entrainment (to a limit of approximately 6% air), than by variations in any other concrete mix property investigated.

8.2 Recommendations For Future Research

The following recommendations are made for future research.

(1) An investigation to verify or disprove the indication that concrete durability is independent of cement content, provided that the air content exceeds a minimum value.

(2) An investigation based on a comparison of freeze-thaw data obtained from the equipment at the University of Alberta, and data from Powers' semi-rational test method.

(3) An investigation to establish the form of relationship between concrete durability and void spacing factor, for very low (less than 0.005 inch), and very high (greater than 0.030 inch) spacing factors.

(4) Investigations to determine the characteristics of air entrained with entraining agents other than "Darex", and under different mixing, casting, and vibrating conditions than used in this investigation.

(5) An investigation to explain the discrepancy between air
    contents measured in fresh concrete (by A.S.T.M. C 231) and
    those obtained for hardened concrete (by A.S.T.M. C 457).
    Specifically, the effect of vibration on air content of
    concrete should be investigated.

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LIST OF REFERENCES

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APPENDIX "A"

SAMPLE DATA SHEETS

A.1 Compressive Strength Testing

A.2 Freeze-Thaw Testing

A.3 Microscopic Analysis

A.1

IVERSITY OF ALBERTA

RTMENT OF CIVIL ENGINEERING

NCRETE LABORATORY

PROJECT ___THESIS___

DATE ___9 SEPT. 1963___

ENG.-TECH. ___WILLIAMSON___

COMPRESSIVE STRENGTH OF CONCRETE CYLINDERS

DIAMETER __3.0 in.__ LENGTH- __6.0 in.__ AREA __7.067 sq. in.__

AGE OF TEST — __28 days__

DESCRIPTION	NUMBER	MAX. LOAD POUNDS	AVE. MAX. LOAD-LBS.	AVE. STRESS P.S.I.
400 - 8.3	1	11,800		
	2	13,100		
	3	12,800	11,800	1670
	4	9,500		
550 - 8.2	1	16,700		
	2	17,800		
	3	18,900	18,050	2550
	4	18,800		
700 -7.2	1	25,100		
	2	20,600		
	3	23,000	23,300	3300
	4	24,500		
400 - 8.7	1	10,800		
	2	12,700		
	3	11,400	11,600	1640
	4	11,500		
550 - 9.0	1	16,100		
	2	15,600		
	3	19,500	16,650	2360
	4	15,400		
700 - 8.8	1	23,300		
	2	22,900		
	3	18,800	22,000	3110
	4	23,000		

DEPARTMENT OF CIVIL ENGINEERING
CONCRETE LABORATORY

Project THESIS
Eng.-Technician WILLIAMSON
Date 30 AUG. TO 25 SEPT. 1963

Description of cement and aggregate: Normal portland cements; 3/4-inch maximum size aggregate:

BEAM DESCRIPTION

Date	No. of Cycles		1 — 400-8.9 (1)	2 — 400-8.9 (2)	3 — 400-8.7 (1)	4 — 400-8.7 (2)	5 — 550-8.2 (1)	6 — 550-8.2 (2)	7 — 550-9.0 (1)	8 — 550-9.0 (2)	9 — 700-7.9 (1)	10 — 700-7.9 (2)	11 — 700-8.8 (1)	12 — 700-8.8 (?)
30Aug. '63	0	FTF / P_c	1900 / 100%	1910 / 100%	1950 / 100%	1970 / 100%	2050 / 100%	2050 / 100%	2040 / 100%	2060 / 100%	2020 / 100%	2130 / 100%	2200 / 100%	2180 / 100%
3 Sept. '63	46	FTF / P_c	1800 / 89.6%	1800 / 89.0%	1830 / 88.0%	1850 / 88.1%	1880 / 84.1%	1910 / 86.9%	1950 / 91.5%	1940 / 88.8%	1930 / 85.1%	1970 / 85.5%	2050 / 86.8%	2040 / 87.6%
9 Sept. '63	118	FTF / P_c	1780 / 88.0%	1800 / 89.0%	1820 / 87.0%	1850 / 88.1%	1880 / 84.1%	1910 / 86.9%	1930 / 89.5%	1930 / 87.5%	1930 / 85.1%	1970 / 85.5%	2050 / 86.8%	2040 / 87.6%
13Sept. '63	163	FTF / P_c	1780 / 88.0%	1790 / 87.8%	1800 / 85.2%	1840 / 87.5%	1880 / 84.1%	1900 / 86.1%	1930 / 89.5%	1900 / 85.0%	1920 / 84.4%	1970 / 85.5%	2040 / 86.0%	2040 / 87.6%
17Sept. '63	216	FTF / P_c	1780 / 88.0%	1790 / 87.8%	1780 / 83.2%	1840 / 87.5%	1880 / 84.1%	1900 / 86.1%	1930 / 89.5%	1880 / 83.2%	1920 / 84.4%	1970 / 85.5%	2040 / 86.0%	2040 / 87.6%
23Sept. '63	289	FTF / P_c	1760 / 85.8%	1760 / 84.7%	1770 / 82.2%	1840 / 87.5%	1870 / 83.0%	1890 / 85.0%	1920 / 88.8%	1880 / 83.3%	1910 / 83.2%	1960 / 84.4%	2030 / 85.1%	2040 / 87.4%
25Sept. '63	312	FTF / P_c	1760 / 85.8%	1760 / 84.7%	1770 / 82.2%	1840 / 87.5%	1870 / 83.0%	1890 / 85.0%	1920 / 88.8%	1880 / 83.3%	1910 / 83.2%	1960 / 84.4%	2030 / 85.1%	2040 / 87.4%
D.F.		FTF / P_c	85.8%		84.7%		84.0%		86.0%		83.8%		86.3%	

UNIVERSITY OF ALBERTA DEPARTMENT OF CIVIL ENGINEERING CONCRETE LABORATORY	PROJECT ___THESIS___ DATE ___22 AUGUST, 1963___ TECH. ENG. ___WILLIAMSON___

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___400 - 8.9___ SIZE $3\frac{1}{2}$" x $4\frac{1}{2}$" x 1" SOURCE ___Beam - $3\frac{1}{2}$"x$4\frac{1}{2}$"x16"___

Water—cement ratio = 0.610 (by weight); paste content by volume = 22.1%

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	31	3.2	120	13	671	55.3	1560
2	80	7.1	240	14	723	58.6	1680
3	124	12.5	360	15	776	61.4	1800
4	179	16.6	480	16	810	66.2	1920
5	221	21.0	600				
6	284	24.8	720				
7	338	31.2	840				
8	419	34.7	960				
9	472	38.3	1080				
10	516	41.8	1200				
11	550	45.7	1320				
12	632	51.1	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$$\bar{l} = \frac{P_u R_u}{N} = \frac{1}{20} \cdot \frac{66.2}{810} = 0.00408"$$

$$T = P_u R_u + P_m R_m = \frac{1}{20}(1920+66.2) = 99.31"$$

$$n = \frac{N}{T} = \frac{810}{99.31} = 8.17 \text{ per inch}$$

$$A = 100nl = \frac{100 \times 8.17 \times 0.00408}{} = 3.33\%$$

$$\alpha = \frac{4}{l} = \frac{4}{0.00408} = 980 \text{ su. in./cu.in}$$

$$\bar{L} = \frac{P}{400n} \qquad (\frac{P}{A} < 4.33)$$

$$\bar{L} = \frac{3}{\alpha}\left[1.4\left(\frac{P}{A}+1\right)^{1/3} - 1\right] (\frac{P}{A} > 4.33)$$

$$= \frac{3}{980}\left(1.4\left(7.64\right)^{1/3} - 1\right)$$

$$= 0.00538"$$

APPENDIX "B"

FREEZE-THAW DATA
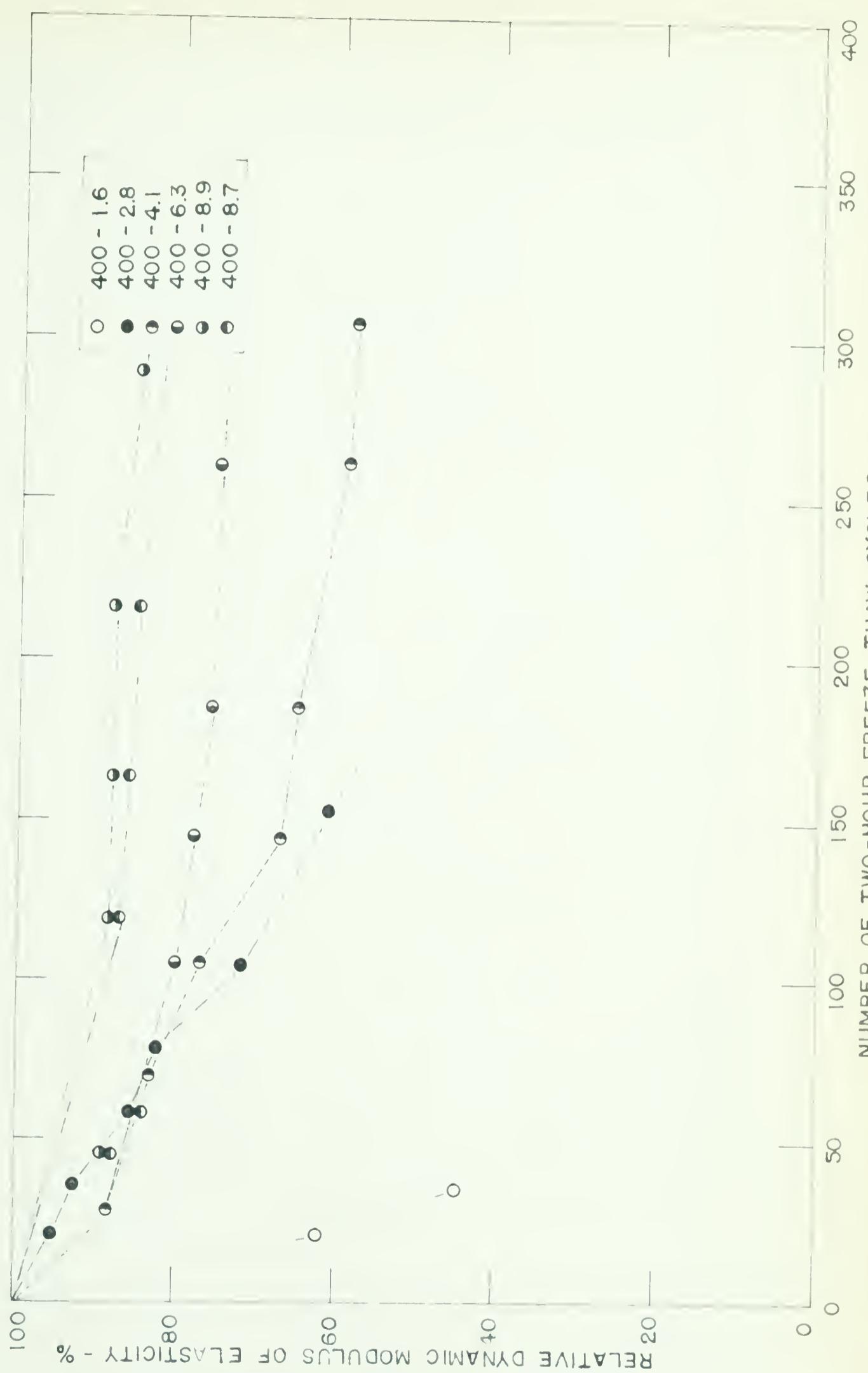
FIGURE B.1 - Relationship Between Relative Dynamic Modulus of Elasticity
And Number of Freeze-Thaw Cycles -Cement Content 400 lb. per cu. yd.
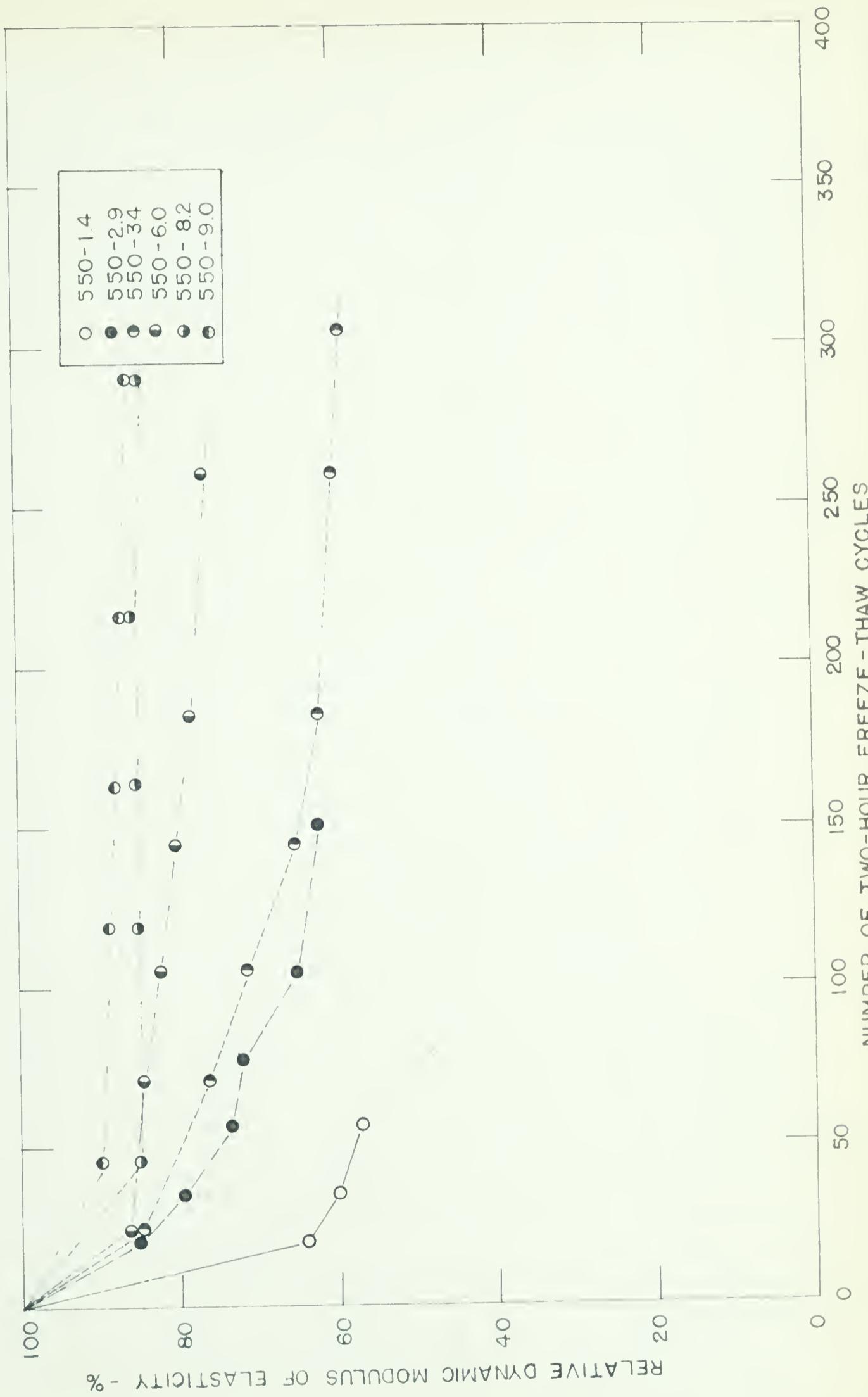
FIGURE B.2 - Relationship Between Relative Dynamic Modulus of Elasticity And Number of Freeze-Thaw Cycles - Cement Content 550 lb. per cu. yd.
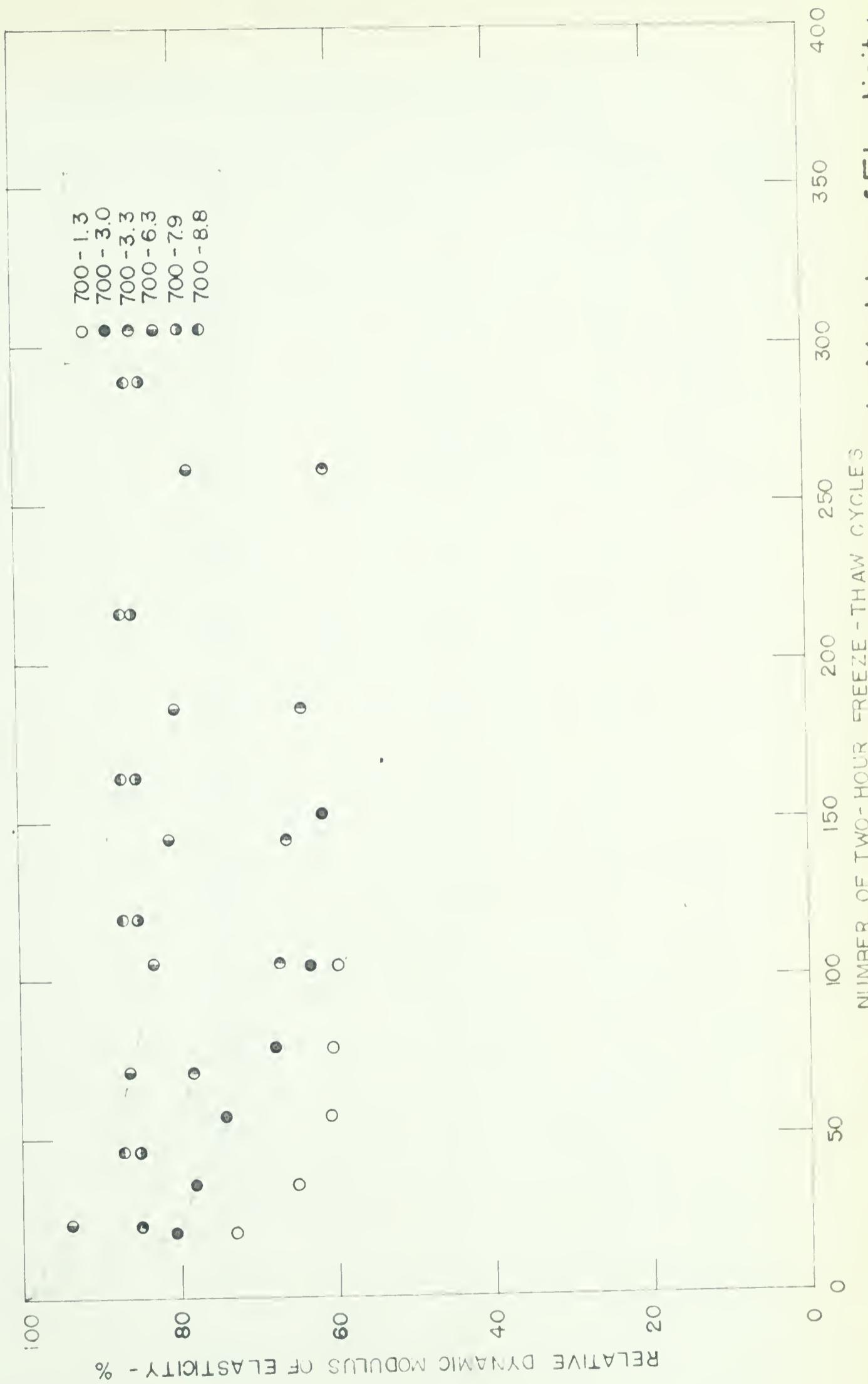
FIGURE B.3 - Relationship Between Relative Dynamic Modulus of Elasticity And Number of Freeze-Thaw Cycles -Cement Content 700 lb. per cu. yd.

TABLE B.1

WEIGHT LOSS DURING FREEZE-THAW TESTING

MIX	ORIGINAL SAMPLE gms.	FINAL WT. gms.	WT. LOSS gms.	AV. WT. LOSS gms.
400 - 1.6	9704	8728	976	
	9685	8971	714	845
550 - 1.4	9774	9355	419	
	9791	9280	511	465
700 - 1.3	9814	9536	278	
	9788	9574	214	246
400 - 2.8	9674	8910	764	
	9713	9037	676	720
550 - 2.9	9780	9374	406	
	9769	9345	424	415
700 - 3.0	9814	9575	239	
	9836	9631	205	222
400 - 4.1	9606	9110	496	
	9698	9279	419	457
550 - 3.4	9778	9594	184	
	9664	9501	163	173
700 - 3.3	9801	9724	77	
	9916	9848	68	73
400 - 6.3	9336	9036	300	
	9394	9149	245	272
550 - 6.0	9433	9278	155	
	9366	9219	147	151
700 - 6.3	9540	9466	74	
	9462	9394	68	71
400 - 8.9	9092	8864	228	
	9042	8788	254	241
550 - 8.2	9233	9097	136	
	9202	9080	122	129

TABLE B.1 Con't.

MIX	ORIGINAL SAMPLE gms.	FINAL WT. gms.	WT. LOSS gms.	AV. WT. LOSS gms.
700 - 7.9	9392 9397	9323 9332	69 65	67
400 - 8.7	9260 9153	9045 8914	215 239	227
550 - 9.0	9210 9272	9081 9173	129 99	114
700 - 8.8	9614 9552	9555 9481	59 71	65

APPENDIX "C"

MICROSCOPIC ANALYSIS TEST DATA

UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE LABORATORY

PROJECT ___THESIS___ C.1
DATE ___11 JULY , 1963___
TECH. ENG. ___WILLIAMSON___

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___400 - 2.6___ SIZE $3\frac{1}{2}" \times 4\frac{1}{2}" \times 1"$ SOURCE ___Beam - $3\frac{1}{2}"\times4\frac{1}{2}"\times16"$___

Water-Cement ratio = 0.853 (by weight); paste content by volume = 0.271

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	2	0.4	120	13	57	17.9	1560
2	5	1.8	240	14	60	19.2	1680
3	8	3.6	360	15	64	20.2	1800
4	13	6.0	480	16	65	21.1	1920
5	17	6.7	600				
6	22	7.5	720				
7	29	8.8	840				
8	31	9.9	960				
9	40	10.7	1080				
10	44	12.4	1200				
11	47	13.6	1320				
			1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$$\bar{l} = \frac{PuRu}{N} = \frac{1}{20} \cdot \frac{21.1}{65} = 0.01625"$$

$$T = PuRu + PmRm = \frac{1/20 \, (1941.1)}{} = 97.06"$$

$$n = \frac{N}{T} = 65/97.06 = 0.671 \text{ per inch}$$

$$A = 100nl = \frac{100 \times 0.671 \times 0.01625}{} = 1.09\%$$

$$\alpha = \frac{4}{\bar{l}} = 4/0.01625 = 246 \text{ sq.in./cu.in.}$$

$$\bar{L} = \frac{p}{400n} \qquad (\frac{p}{A} < 4.33)$$

$$\bar{L} = \frac{3}{\alpha}\left[1.4\left(\frac{p}{A}+1\right)^{1/3} - 1\right](\frac{p}{A}) 4.33)$$

$$= 3/246\left[1.4(25.9)^{1/3} - 1\right]$$

$$= 0.0382"$$

UNIVERSITY OF ALBERTA DEPARTMENT OF CIVIL ENGINEERING CONCRETE LABORATORY	PROJECT ___THESIS___ DATE ___11 JULY , 1963___ TECH. ENG. ___WILLIAMSON___

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___550 - 1.4___ SIZE ___3½"x4½"x1"___ SOURCE ___Beam - 3½"x4½"x16"___

Water-cement ratio = 0.561 (by weight); paste content = 0.285

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	1	0.2	120	13	46	9.8	1560
2	4	0.9	240	14	48	10.4	1680
3	9	1.6	360	15	50	11.1	1800
4	16	2.1	480	16	51	12.0	1920
5	21	3.4	600				
6	25	4.2	720				
7	27	4.8	840				
8	31	5.4	960				
9	34	6.1	1080				
10	39	6.9	1200				
11	41	7.5	1320				
12	44	9.0	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$\bar{l} = \frac{Pu Ru}{N} = \frac{1}{20} \cdot \frac{12.0}{51} = 0.01170"$

$T = Pu Ru + Pm Rm = \dfrac{1/20 \ (1932.0)}{96.60"}$

$n = \frac{N}{T} = 51/96.60 = 0.528$ per inch

$A = 100 n l = \frac{100 \times 0.528 \times 0.0117}{} = 0.617\%$

$\alpha = \frac{4}{l} = 4/ 0.0117 = 341$ sq. in./cu.in.

$\bar{L} = \frac{P}{400 n}$ $\qquad (\frac{P}{A} < 4.33)$

$\bar{L} = \frac{3}{\alpha} \left[1.4 \ (\frac{P}{A} + 1)^{1/3} - 1 \right] (\frac{P}{A} > 4.33)$

$= 3/341 \left[1.4 \ (47.2)^{1/3} - 1 \right]$

$= 0.0358"$

UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE LABORATORY

PROJECT ___THESIS___
DATE ___11 JULY , 1963___
TECH. ENG. ___WILLIAMSON___

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___700 - 1.3___ SIZE $3\frac{1}{2}"$ x $4\frac{1}{2}"$ x 1" SOURCE ___Beam - $3\frac{1}{2}"$x$4\frac{1}{2}"$x16"___

Water-cement ratio = 0.427 (by weight); paste content by volume = 0.312

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	3	1.0	120	13	36	6.4	1560
2	4	1.3	240	14	39	7.0	1680
3	6	1.8	360	15	41	7.5	1800
4	9	1.9	480	16	45	8.4	1920
5	14	2.3	600				
6	16	2.9	720				
7	17	3.3	840				
8	20	3.9	960				
9	24	4.4	1080				
10	26	4.9	1200				
11	29	5.4	1320				
12	34	6.1	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$\bar{l} = \dfrac{Pu Ru}{N} = \dfrac{1}{20} \cdot \dfrac{8.4}{45} = 0.00938$ "

$T = Pu Ru + Pm Rm = \dfrac{1/20\ (1928.4)}{} = 96.42$"

$n = \dfrac{N}{T} = 45/96.42 = 0.468$ per inch

$A = 100 n l = \dfrac{100 \times 0.468 \times 0.00938}{} = 0.439\%$

$\alpha = \dfrac{4}{\bar{l}} = 4/0.00938 = 427$ sq.in./cu.in.

$\bar{L} = \dfrac{p}{400n}$ $(\dfrac{p}{A} < 4.33)$

$\bar{L} = \dfrac{3}{\alpha}\left[1.4\left(\dfrac{p}{A} + 1\right)^{1/3} - 1 \right] (\dfrac{p}{A} > 4.33)$

$= 3/427\left[1.4\left(72.1\right)^{1/3} - 1 \right]$

$= 0.0340$"

UNIVERSITY OF ALBERTA	PROJECT THESIS C-4
DEPARTMENT OF CIVIL ENGINEERING	DATE 12 JULY, 1963
CONCRETE LABORATORY	TECH. ENG. WILLIAMSON

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. 400 - 2.8   SIZE 3½"x4½"x1"   SOURCE Beam - 3½"x4½"x16"

Water-cement ratio = 0.734 (by weight); paste content by volume = 0.252

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	2	0.6	120	13	36	5.5	1560
2	5	1.3	240	14	40	6.2	1680
3	8	1.5	360	15	42	6.9	1800
4	11	1.9	480	16	45	7.7	1920
5	14	2.2	600				
6	16	2.5	720				
7	19	2.9	840				
8	20	3.3	960				
9	26	3.8	1080				
10	29	4.2	1200				
11	31	4.8	1320				
12	33	5.1	1440				

$\bar{i}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
$\propto$ = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$\bar{i} = \dfrac{Pu Ru}{N} = \dfrac{1}{20} \cdot \dfrac{7.7}{45} = 0.00840"$

$\dfrac{1/20 (1927.7)}{}$

$T = Pu Ru + Pm Rm = 96.38"$

$n = \dfrac{N}{T} = 45/96.38 = 0.477$ per inch

$A = 100 n i = \dfrac{100 \times 0.477 \times 0.0084}{} = 0.400\%$

$\propto = \dfrac{4}{i} = 4/0.0084 = 476$ sq.in./cu.in.

$\bar{L} = \dfrac{P}{400 n}$ ($\dfrac{p}{A} < 4.33$)

$\bar{L} = \dfrac{3}{\propto}\left[1.4 \left(\dfrac{P}{A} + 1\right)^{1/3} - 1\right]$ ($\dfrac{p}{A} > 4.33$)

$= 3/476\left[1.4 (64.0)^{1/3} - 1\right]$

$= 0.0291"$

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. __550 - 2.9__ SIZE __$3\frac{1}{2}"x4\frac{1}{2}"x1"$__ SOURCE __Beam - $3\frac{1}{2}"x4\frac{1}{2}"x16"$__

Water-cement ratio = 0.546 (by weight); paste content by volume = 0.285

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	6	0.8	120	13	64	9.8	1560
2	9	1.1	240	14	67	10.8	1680
3	11	1.8	360	15	69	11.1	1800
4	15	2.1	480	16	71	11.4	1920
5	19	2.7	600				
6	22	3.3	720				
7	29	4.6	840				
8	39	6.0	960				
9	45	6.8	1080				
10	52	7.7	1200				
11	58	8.9	1320				
12	61	9.2	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
P = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$\bar{l} = \dfrac{Pu Ru}{N} \cdot \dfrac{1}{20} \cdot \dfrac{11.4}{71} = 0.00805"$

$$\dfrac{1/20 (1931.4)}{}$$
T = Pu Ru + Pm Rm = 96.57"

n = $\dfrac{N}{T}$ = 71/96.52 = 0.736 per inch

$$\dfrac{100 \times 0.736 \times 0.00805}{}$$
A = 100 n l = 0.592%

$\alpha = \dfrac{4}{l} = 4/0.00805 = 498$ sq.in./cu.in

$\bar{L} = \dfrac{P}{400n}$ $\qquad (\frac{P}{A} < 4.33)$

$\bar{L} = \dfrac{3}{\alpha}\left[1.4\left(\dfrac{P}{A}+1\right)^{1/3} - 1\right] (\frac{P}{A} > 4.33)$

$= 3/498\left[1.4 (49.2)^{1/3} - 1\right]$

$= 0.0249"$

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DEPARTMENT OF CIVIL ENGINEERING
CONCRETE LABORATORY

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___700 - 3.0___ SIZE ___3½"x4½"x1"___ SOURCE ___Beam - 3½"x4½"x16"___

Water-cement ratio = 0.615 (by weight); paste content by volume = 0.310

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	10	1.4	120	13	104	13.5	1560
2	17	2.1	240	14	116	14.9	1680
3	25	2.8	360	15	119	16.2	1800
4	34	3.7	480	16	122	18.0	1920
5	39	4.5	600				
6	47	6.1	720				
7	54	7.5	840				
8	59	8.8	960				
9	65	9.7	1080				
10	79	10.4	1200				
11	91	11.6	1320				
12	96	12.2	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$$\bar{l} = \frac{Pu Ru}{N} \cdot \frac{1}{20} \cdot \frac{18.0}{122} = 0.00738"$$

$$T = Pu Ru + Pm Rm = \frac{1/20 (1938.0)}{} = 96.90"$$

$$n = \frac{N}{T} = 122/96.90 = 1.26 \text{ per inch}$$

$$A = 100 n l = \frac{100 \times 1.26 \times 0.00738}{} = 0.965\%$$

$$\alpha = \frac{4}{l} = 4/0.00738 = 542 \text{ sq.in./cu.in.}$$

$$\bar{L} = \frac{p}{400n} \qquad (\frac{p}{A} < 4.33)$$

$$\bar{L} = \frac{3}{\alpha} \left[1.4 \left(\frac{p}{A} + 1\right)^{1/3} - 1 \right] \quad (\frac{p}{A} > 4.33)$$

$$= 3/542 \left[1.4 \ (33.2)^{1/3} - 1 \right]$$

$$= 0.0194"$$

UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE LABORATORY

PROJECT ___THESIS___
DATE ___4 AUGUST, 1963___
TECH. ENG. ___WILLIAMSON___

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___400 - 4.1___ SIZE $3\frac{1}{2}"x4\frac{1}{2}"x1"$ SOURCE Beam - $3\frac{1}{2}"x4\frac{1}{2}"x16"$

Water-cement ratio = 0.724 (by weight); paste content by volume = 0.250

LINEAR TRAVERSE METHOD

averse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	14	2.9	120	13	261	33.7	1560
2	31	6.1	240	14	287	36.2	1680
3	48	8.8	360	15	304	39.9	1800
4	61	11.7	480	16	327	44.0	1920
5	79	13.4	600				
6	98	16.2	720				
7	125	18.6	840				
8	149	20.9	960				
9	168	23.3	1080				
10	183	26.0	1200				
11	207	28.8	1320				
12	232	31.4	1440				

$\bar{i}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$\bar{i} = \frac{PuRu}{N} = \frac{1}{20} \cdot \frac{44.0}{327} = 0.00672"$

$T = PuRu + PmRm = \frac{1/20 (1964.0)}{98.20"}$

$n = \frac{N}{T} = 327/98.20 = 3.33$ per inch

$A = 100n\bar{i} = \frac{100 \times 3.33 \times 0.00672}{} = 2.24\%$

$\alpha = \frac{4}{\bar{i}} = 4/0.00672 = 595$ sq.in./cu.in.

$\bar{L} = \frac{p}{400n}$ $(\frac{p}{A} < 4.33)$

$\bar{L} = \frac{3}{\alpha}\left[1.4 (\frac{p}{A}+1)^{1/3} - 1\right] (\frac{p}{A} > 4.33)$

$= 3/595 \left[1.4 (12.1)^{1/3} - 1\right]$

$= 0.0112"$

UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE LABORATORY

PROJECT _____ THESIS
DATE _____ 4 AUGUST, 1963
TECH. ENG. _____ WILLIAMSON

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. _____ 550 - 3.4 _____ SIZE $3\frac{1}{2}"x4\frac{1}{2}"x1"$ _____ SOURCE Beam - $3\frac{1}{2}"x4\frac{1}{2}"x16"$

Water-cement ratio = 0.498 (by weight); paste content by volume = 0.274

LINEAR TRAVERSE METHOD

verse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	27	2.9	120	13	416	48.8	1560
2	64	5.7	240	14	451	54.1	1680
3	98	9.2	360	15	476	57.0	1800
4	122	13.1	480	16	492	62.2	1920
5	151	17.6	600				
6	179	22.7	720				
7	204	25.9	840				
8	261	29.8	960				
9	297	32.4	1080				
10	326	37.9	1200				
11	364	40.0	1320				
12	389	43.8	1440				

$\overline{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$$\overline{l} = \frac{Pu Ru}{N} = \frac{1}{20} \cdot \frac{62.2}{492} = 0.00633"$$

$$T = Pu Ru + Pm Rm = \frac{1/20 \ (1982.2)}{99.11"}$$

$$n = \frac{N}{T} = 492/99.11 = 4.97 \text{ per inch}$$

$$A = 100nl = \frac{100 \times 4.97 \times 0.00633}{3.15\%}$$

$$\alpha = \frac{4}{\overline{l}} = 4/0.00633 = 632 \text{ sq.in./cu.in.}$$

$$\bar{L} = \frac{p}{400n} \qquad (\frac{p}{A} < 4.33)$$

$$\bar{L} = \frac{3}{\alpha} \left[1.4 \ (\frac{p}{A} + 1)^{4/3} - 1 \right] (\frac{p}{A} > 4.33)$$

$$= 3/632 \left[1.4 \ (9.7)^{1/3} - 1 \right]$$

$$= 0.0094 "$$

UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE LABORATORY

PROJECT _____ THESIS _____
DATE ____ 4 AUGUST 1963 ____
TECH. ENG. ____ WILLIAMSON ____

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___ 700 - 3.3 ___ SIZE __ 3½"x4½"x1" ___ SOURCE __ Beam - 3½"x4½"x16" __

Water-cement ratio = 0.385 (by weight); paste content by volume = 0.302

LINEAR TRAVERSE METHOD

verse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	37	3.9	120	13	479	53.6	1560
2	81	8.2	240	14	510	58.1	1680
3	116	12.2	360	15	539	61.9	1800
4	141	16.0	480	16	577	68.3	1920
5	178	19.6	600				
6	214	23.1	720				
7	243	27.8	840				
8	278	33.6	960				
9	309	37.4	1080				
10	348	41.6	1200				
11	392	45.0	1320				
12	436	49.6	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$\bar{l} = \frac{Pu Ru}{N} = \frac{1}{20} \cdot \frac{68.3}{577} = 0.00590"$

$\frac{1/20 (1988.3)}{}$

T = PuRu + PmRm = 99.42"

n = $\frac{N}{T}$ = 577/99.42 = 5.81 per inch

A = 100nl = $\frac{100 \times 5.81 \times 0.00590}{3.43\%}$

$\alpha = \frac{4}{\bar{l}} = 4/0.00590 = 678$ sq.in./cu.in.

$\bar{L} = \frac{P}{400n}$　　　　$(\frac{P}{A} < 4.33)$

$\bar{L} = \frac{3}{\alpha} \left[1.4 (\frac{P}{A} + 1)^{1/3} - 1 \right] (\frac{P}{A}) 4.33)$

= 3/678 $\left[1.4 (9.81)^{1/3} - 1 \right]$

= 0.00880"

UNIVERSITY OF ALBERTA	PROJECT ___ THESIS ___
DEPARTMENT OF CIVIL ENGINEERING	DATE ___ 5 AUGUST, 1963
CONCRETE LABORATORY	TECH. ENG. ___ WILLIAMSON

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___ 400 - 6.3 ___ SIZE $3\frac{1}{2}"x4\frac{1}{2}"x1"$ ___ SOURCE ___ Beam - $3\frac{1}{2}"x4\frac{1}{2}"x16"$

Water-cement ratio = 0.620 (by weight); paste content by volume = 0.228

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	42	4.6	120	13	616	67.0	1560
2	96	9.8	240	14	694	78.1	1680
3	141	13.9	360	15	739	82.2	1800
4	194	16.4	480	16	876	89.4	1920
5	239	23.6	600				
6	288	28.0	720				
7	331	33.3	840				
8	380	38.4	960				
9	409	43.3	1080				
10	462	48.9	1200				
11	511	54.6	1320				
12	563	61.3	1440				

$\bar{i}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$$\bar{i} = \frac{PuRu}{N} = \frac{1}{20} \cdot \frac{89.4}{876} = 0.00507"$$

$$T = PuRu + PmRm = \frac{1/20 \ (2009.4)}{} = 100.47"$$

$$n = \frac{N}{T} = 876/100.47 = 8.72 \text{ per inch}$$

$$A = 100n\bar{i} = \frac{100 \times 8.72 \times 0.00507}{} = 4.44\%$$

$$\alpha = \frac{4}{\bar{i}} = 4/0.00507 = 789 \text{ sq.in./cu.in}$$

$$\bar{L} = \frac{P}{400n} \qquad (\frac{P}{A} < 4.33)$$

$$\bar{L} = \frac{3}{\alpha}\left[1.4\left(\frac{P}{A}+1\right)^{4/3} - 1\right] (\frac{P}{A} > 4.33)$$

$$= 3/789\left[1.4\ (6.13)^{4/3} - 1\right]$$

$$= 0.00592"$$

UNIVERSITY OF ALBERTA	PROJECT	THESIS
DEPARTMENT OF CIVIL ENGINEERING	DATE	5 AUGUST, 1963
CONCRETE LABORATORY	TECH. ENG.	WILLIAMSON

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. __550 - 6.0__   SIZE __3½"x4½"x1"__   SOURCE __Beam - 3½"x4½"x16"__

Water-cement ratio = 0.473 (by weight); paste content by volume = 0.263

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	43	3.9	120	13	729	59.6	1560
2	97	8.2	240	14	798	63.9	1680
3	141	13.1	360	15	841	68.8	1800
4	190	17.2	480	16	902	75.6	1920
5	237	21.6	600				
6	289	26.8	720				
7	352	30.9	840				
8	441	36.8	960				
9	494	41.9	1080				
10	547	44.7	1200				
11	603	48.3	1320				
12	669	52.8	1440				

l = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$l = \frac{PuRu}{N} = \frac{1}{20} \cdot \frac{75.6}{902} = 0.00419"$

$T = PuRu + PmRm = \frac{1/20\ (1995.6)}{} = 99.78"$

$n = \frac{N}{T} = 902/99.78 = 9.05$ per inch

$A = 100nl = \frac{100 \times 9.05 \times 0.00419}{} = 3.80\%$

$\alpha = \frac{4}{l} = 4/0.00419 = 954$ sq.in./cu.in.

$\bar{L} = \frac{P}{400n}$ $(\frac{P}{A} < 4.33)$

$\bar{L} = \frac{3}{\alpha} \left[1.4 (\frac{P}{A} + 1)^{1/3} - 1 \right] (\frac{P}{A} > 4.33)$

$= 3/954 \left[1.4\ (7.93)^{1/3} - 1 \right]$

$= 0.00564"$

UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
CONCRETE LABORATORY

PROJECT _____
DATE _____
TECH. ENG. _____

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___700 - 6.3___ SIZE $3\frac{1}{2}" \times 4\frac{1}{2}" \times 1"$ _____ SOURCE ___$3\frac{1}{2}" \times 4\frac{1}{2}" \times 16"$ Beam___

Water-cement ratio = 0.392 (by weight); paste content by volume = 0.297

LINEAR TRAVERSE METHOD

averse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	61	5.4	120	13	836	64.6	1560
2	117	9.6	240	14	898	70.2	1680
3	184	13.9	360	15	984	75.6	1800
4	336	18.3	480	16	1080	82.5	1920
5	402	23.7	600				
6	447	29.1	720				
7	489	34.4	840				
8	522	39.8	960				
9	579	45.0	1080				
10	633	49.3	1200				
11	682	54.7	1320				
12	751	59.2	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$$\bar{l} = \frac{Pu Ru}{N} = \frac{1}{20} \cdot \frac{82.5}{1080} = 0.00382"$$

$$T = Pu Ru + Pm Rm = \frac{1/20 \ (2002.5)}{} = 100.12"$$

$$n = \frac{N}{T} = 1080/100.12 = 10.79 \text{ per inch}$$

$$A = 100 n l = \frac{100 \times 0.00382 \times 10.79}{} = 4.12\%$$

$$\alpha = \frac{4}{l} = 4/0.00382 = 1040 \text{ sq.in./cu.in.}$$

$$L = \frac{P}{400n} \qquad (\frac{P}{A} < 4.33)$$

$$\bar{L} = \frac{3}{\alpha} \left[1.4 \left(\frac{P}{A} + 1\right)^{1/3} - 1 \right] (\frac{P}{A} > 4.33)$$

$$= 3/1040 \left[1.4 \ (8.21)^{1/3} - 1 \right]$$

$$= 0.00530"$$

UNIVERSITY OF ALBERTA DEPARTMENT OF CIVIL ENGINEERING CONCRETE LABORATORY	PROJECT ___THESIS___ DATE ___27 AUGUST, 1963___ TECH. ENG. ___WILLIAMSON___

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___400 - 8.9___ SIZE $3\frac{1}{2}"x4\frac{1}{2}"x1"$ SOURCE ___Beam - $3\frac{1}{2}"x4\frac{1}{2}"x16"$___

Water-cement ratio = 0.610 (by weight); paste content by volume = 0.221

LINEAR TRAVERSE METHOD

verse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	31	3.2	120	13	671	55.3	1560
2	80	7.1	240	14	723	58.6	1680
3	224	12.5	360	15	776	61.4	1800
4	179	16.6	480	16	810	66.2	1920
5	221	21.0	600				
6	284	24.8	720				
7	338	31.2	840				
8	419	34.7	960				
9	472	38.3	1080				
10	516	41.8	1200				
11	559	45.9	1320				
12	612	51.1	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$\bar{l} = \dfrac{PuRu}{N} = \dfrac{1}{20} \cdot \dfrac{66.2}{810} = 0.00408"$

$\dfrac{1}{20}(1986.2)$

$T = PuRu + PmRm = 99.31"$

$n = \dfrac{N}{T} = 810/99.31 = 8.17$ per inch

$A = 100nl = \dfrac{100 \times 8.17 \times 0.00408}{} = 3.33\%$

$\alpha = \dfrac{4}{l} = 4/0.00408 = 980$ sq.in./cu.in.

$\bar{L} = \dfrac{P}{400n}$ $(\frac{P}{A} < 4.33)$

$\bar{L} = \dfrac{3}{\alpha}\left[1.4\left(\dfrac{P}{A}+1\right)^{1/3} - 1\right] (\frac{P}{A} > 4.33)$

$= 3/980\left[1.4(7.64)^{1/3} - 1\right]$

$= 0.00538"$

UNIVERSITY OF ALBERTA
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CONCRETE LABORATORY

PROJECT _____ THESIS
DATE ____ 27 AUGUST, 1963
TECH. ENG. __ WILLIAMSON

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___ 550 - 3.2 ___ SIZE $3\frac{1}{2}"x4\frac{1}{2}"x1"$ ___ SOURCE Beam - $3\frac{1}{2}"x4\frac{1}{2}"x16"$

Water-cement ratio = 0.476 (by weight); paste content by volume = 0.260

LINEAR TRAVERSE METHOD

averse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	69	4.4	120	13	961	70.4	1560
2	171	9.7	240	14	1040	76.1	1680
3	214	14.2	360	15	1091	82.8	1800
4	289	19.0	480	16	1131	89.6	1920
5	352	23.4	600				
6	414	29.4	720				
7	470	33.6	840				
8	552	41.9	960				
9	629	46.3	1080				
10	716	51.7	1200				
11	802	57.2	1320				
12	879	62.4	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$\bar{l} = \frac{PuRu}{N} = \frac{1}{20} \cdot \frac{89.6}{1131} = 0.00396"$

$T = PuRu + PmRm = \frac{1/20\ (2009.6)}{} = 100.48"$

$n = \frac{N}{T} = 1131/100.48 = 11.25$ per inch

$A = 100nl = 100\times11.25\times0.00396$
$= 4.46\%$

$\alpha = \frac{4}{\bar{l}} = 4/0.00396 = 1010$ sq.in./cu.in.

$\bar{L} = \frac{p}{400n}$ $\qquad (\frac{p}{A} < 4.33)$

$\bar{L} = \frac{3}{\alpha}\left[1.4\left(\frac{p}{A}+1\right)^{1/3} - 1\right] (\frac{p}{A} > 4.33)$

$= 3/1010 \quad 1.4\ (6.82) \quad -1$

$= 0.00493"$

UNIVERSITY OF ALBERTA	PROJECT ___THESIS___
DEPARTMENT OF CIVIL ENGINEERING	DATE ___27 AUGUST, 1963___
CONCRETE LABORATORY	TECH. ENG. ___WILLIAMSON___

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___700 - 0.9___   SIZE $3\frac{1}{2}"x4\frac{1}{2}"x1"$ SOURCE Beam - $3\frac{1}{2}"x4\frac{1}{2}"x16"$

Water-cement ratio = 0.408 (by weight): paste content by volume = 0.298

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	78	6.9	120	13	1039	74.9	1560
2	163	14.0	240	14	1104	81.4	1680
3	233	19.8	360	15	1163	84.8	1800
4	281	24.4	480	16	1225	89.4	1920
5	349	31.5	600				
6	432	33.5	720				
7	516	38.8	840				
8	602	43.6	960				
9	691	50.2	1080				
10	754	54.3	1200				
11	851	59.3	1320				
12	925	66.3	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
$\propto$ = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$\bar{l} = \frac{PuRu}{N} = \frac{1}{2} \cdot \frac{19.4}{1225} = 0.00365"$

$T = PuRu + PmRm = \frac{1/20 \ (2009.4)}{} = 100.47"$

$n = \frac{N}{T} \quad 1225/100.47 = 12.2$ per inch

$A = 100nl = \frac{100 \times 12.2 \times 0.00365}{} = 4.45\%$

$\propto = \frac{4}{\bar{l}} = 4/0.00365 = 1095$ sq.in./cu.in.

$\bar{L} = \frac{P}{400n} \qquad (\frac{P}{A} < 4.33)$

$\bar{L} = \frac{3}{\propto} \left[1.4 \left(\frac{P}{A} + 1\right)^{1/3} - 1 \right] (\frac{P}{A} > 4.33)$

$= 3/1095 \left[1.4 \ (7.70)^{1/3} - 1 \right]$

$= 0.00482"$

UNIVERSITY OF ALBERTA	PROJECT ___THESIS___
DEPARTMENT OF CIVIL ENGINEERING	DATE ___29 AUGUST, 1963___
CONCRETE LABORATORY	TECH. ENG. ___WILLIAMSON___

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___401 - 8.7___ SIZE ___3½"x4½"x1"___ SOURCE ___Beam - 3½"x4½"x16"___

Water-cement ratio = 0.613 (by weight); paste content by volume = 0.225

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	43	3.4	120	13	917	69.9	1560
2	117	10.3	240	14	1004	73.4	1680
3	198	14.2	360	15	1061	78.8	1800
4	256	15.8	480	16	1102	86.2	1920
5	350	24.0	600				
6	402	29.6	720				
7	450	34.3	840				
8	512	41.4	960				
9	593	45.7	1080				
10	681	51.3	1200				
11	750	56.7	1320				
12	832	62.4	1440				

$\bar{1}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
$\propto$ = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$$\bar{1} = \frac{PuRu}{N} = \frac{1}{20} \cdot \frac{86.2}{1102} = 0.00391"$$

$$\frac{1/20 (2006.2)}{}$$

$$T = PuRu + PmRm = = 100.31"$$

$$n = \frac{N}{T} = 1102/100.31 = 11.0 \text{ per inch}$$

$$A = 100n\bar{1} = 100 \times 11.0 \times 0.00391 = 4.30\%$$

$$\propto = \frac{4}{\bar{1}} = 4/0.00391 = 1025 \text{ sq.in./cu.in.}$$

$$\bar{L} = \frac{P}{400n} \qquad (\frac{P}{A} < 4.33)$$

$$\bar{L} = \frac{3}{\propto} \left[1.4 \left(\frac{P}{A} + 1\right)^{1/3} - 1 \right] (\frac{P}{A} > 4.33)$$

$$= 3/1025 \left[1.4 (6.23)^{1/3} - 1 \right]$$

$$= 0.00461"$$

UNIVERSITY OF ALBERTA	PROJECT ___THESIS___
DEPARTMENT OF CIVIL ENGINEERING	DATE ___29 AUGUST, 1963___
CONCRETE LABORATORY	TECH. ENG. ___WILLIAMSON___

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___550 - 3.0___   SIZE ___3½"x4½"x1"___   SOURCE ___Beam - 3½"x4½"x16"___

Water-cement ratio = 0.493 (by volume); paste content by volume = 0.264

LINEAR TRAVERSE METHOD

verse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	83	5.3	120	13	966	71.2	1560
2	151	9.6	240	14	1039	75.8	1680
3	229	14.7	360	15	1087	78.9	1800
4	314	20.0	480	16	1145	86.0	1920
5	373	25.4	600				
6	480	30.8	720				
7	532	36.8	840				
8	604	45.2	960				
9	677	51.1	1080				
10	739	55.9	1200				
11	814	62.4	1320				
12	845	68.9	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$$\bar{l} = \frac{PuRu}{N} = \frac{1}{20} \cdot \frac{86}{1145} = 0.00377"$$

$$T = PuRu + PmRm = \frac{1/20 \, (2006.0)}{} = 100.30"$$

$$n = \frac{N}{T} = 1145/100.30 = 11.4 \text{ per inch}$$

$$A = 100nl = \frac{100 \times 11.4 \times 0.00377}{} = 4.3\%$$

$$\alpha = \frac{4}{l} = 4/0.00377 = 1060 \text{ sq.in./cu.in.}$$

$$\bar{L} = \frac{P}{400n} \qquad (\frac{P}{A} < 4.33)$$

$$\bar{L} = \frac{3}{\alpha}\left[1.4 \left(\frac{P}{A} + 1\right)^{1/3} - 1\right] (\frac{P}{A} > 4.33)$$

$$= 3/1060 \left[1.4 \, (7.15)^{1/3} - 1\right]$$

$$= 0.00479"$$

UNIVERSITY OF ALBERTA	
DEPARTMENT OF CIVIL ENGINEERING CONCRETE LABORATORY	PROJECT ___THESIS___ DATE ___20 AUGUST, 1963___ TECH. ENG. ___WILLIAMSON___

MICROSCOPIC DETERMINATION OF AIR VOID CONTENT, SPECIFIC SURFACE AND SPACING FACTOR

OF THE AIR VOID SYSTEM IN HARDENED CONCRETE

SAMPLE NO. ___700 - 8.8___ SIZE $3\frac{1}{2}"x4\frac{1}{2}"x1"$ SOURCE ___Beam - $3\frac{1}{2}"x4\frac{1}{2}"x16"$___

Water-cement ratio = 0.417 (by weight); paste content by volume = 0.302

LINEAR TRAVERSE METHOD

Traverse no.	N	Ru	Rm	Traverse no.	N	Ru	Rm
1	82	5.7	120	13	1139	82.4	1560
2	171	11.3	240	14	1180	87.1	1680
3	260	15.8	360	15	1265	91.6	1800
4	356	22.4	480	16	1355	95.7	1920
5	472	27.9	600				
6	547	34.7	720				
7	616	40.6	840				
8	693	49.3	960				
9	771	56.1	1080				
10	830	62.4	1200				
11	972	68.3	1320				
12	1064	75.1	1440				

$\bar{l}$ = average chord intercept of the air void in inches
N = total number of air voids intersected in the entire traverse
Pu = pitch of the upper lead screw in inches per revolution
Ru = total number of revolutions of the upper lead screw
T = total length of traverse in inches
Pm = pitch of main lead screw in inches per revolution
Rm = total number of revolution of the main lead screw
n = average number of air-void sections intercepted per inch
α = specific surface
$\bar{L}$ = spacing factor
p = paste content, per cent by volume of the concrete
A = air void content

CALCULATIONS

$\bar{l} = \dfrac{Pu Ru}{N} = \dfrac{1}{20} \cdot \dfrac{95.7}{1355} = 0.00355"$

$$\dfrac{1/20\ (2015.7)}{}$$

$T = Pu Ru + Pm Rm = 100.78"$

$n = \dfrac{N}{T} = 1355/100.78 = 13.4$ per inch

$A = 100 n l = \dfrac{100 \times 13.4 \times 0.00354}{} = 4.75\%$

$\alpha = \dfrac{4}{l} = 4/0.00354 = 1130$ sq.in./cu.in.

$\bar{L} = \dfrac{P}{400n}$ $\left(\dfrac{P}{A} < 4.33\right)$

$\bar{L} = \dfrac{3}{\alpha}\left[1.4\left(\dfrac{P}{A} + 1\right)^{1/3} - 1 \right]\left(\dfrac{P}{A} > 4.33\right)$

$= 3/1130 \left[1.4\ (7.36)^{1/3} - 1 \right]$

$= 0.00458"$

SOURCE OF SPECIMEN OBTAINED FOR

MICROSCOPIC EXAMINATION

A longitudinal slice of concrete approximately one inch thick was cut from near the center of one beam of each mix for microscopic examination.

The side of the slice prepared for examination was arbitarily chosen, and polished.

The orientation of the slice was noted, so that microscopic examination always proceeded in linear traverses starting from the top of the sample. Each traverse length was approximately seven inches, and the traverses were approximately 1/4 inch apart.